PB84-143916

Water Supply Simulation Model
Volume 1. Model Development

Gates (W. E.) and Associates, Inc., Batavia, OH

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Nov 83

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-143916

EPA-600/2-83-121a
November 1983

WATER SUPPLY SIMULATION MODEL

VOLUME I - MODEL DEVELOPMENT

by

Robert M. Clark
Drinking Water Research Division
Municipal Environmental Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Richard M. Males
W. E. Gates and Associates, Inc.
Batavia, Ohio 45103

Contract No. 68-03-2941

Project Officer

Robert M. Clark
Drinking Water Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-83-121a		PB84 143916

4. TITLE AND SUBTITLE	5. REPORT DATE
WATER SUPPLY SIMULATION MODEL: Volume I. Model Development	November 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Robert M. Clark and R. M. Males	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
W. E. Gates & Associates Batavia, Ohio 45103	11. CONTRACT/GRANT NO.
	Contract 68-03-2941
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Municipal Environmental Research Laboratory - Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268	14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project officer: Robert M. Clark (513)684-7488

16. ABSTRACT

This three-volume report describes the development of a water supply simulation model (WSSM), a system of computer programs that allows for a systematic evaluation of the physical and economic characteristics of a water distribution system in a spatial framework.

The WSSM concept views a water utility as a network overlayed upon a spatial distribution of supply and demand. The model explicitly deals with the relationship of delivered water costs to the service requirements of spatially distributed demand. Once an adequate hydraulic simulation has been made, the model can be used to determine costs, travel time, and contaminant concentrations at various points in the network.

The model has been calibrated and tested on several water supply systems including a small utility in New Vienna, Ohio, and the Kenton County Water District No. 1 in Kenton County, Kentucky. Volume 1 of this study describes the development of the model and its underlying principals. Volume 2 discusses some of the engineering and economic concepts used in developing the model. Volume 3 is a users manual for the model.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
		92
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-03-2941 to W. E. Gates and Associates, Inc. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commerical products does not constitute endoresement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and interplay among its components require a concentrated and integrated attack on the problem.

Research and development is the first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems (1) to prevent, treat, and manage wastewater, solid and hazardous waste, and pollutant discharges from municipal and community sources, (2) to preserve and treat public drinking water supplies, and (3) to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is a product of that research and is a most vital communications link between the research and the user community.

One of the major problems facing the U.S. Enivronmental Protection Agency is meeting the requirements of the Safe Drinking Water Act. The Act emphasizes the need to consider economics in all phases of its implementation. This report presents results from a study on the development of a water supply system simulation model. The model allows the user to evaluate the tradeoffs involved in making decisions concerning system expansion, water production and facility location. It should be useful to water supply managers and planners.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

For the water supply industry, the Safe Drinking Water Act of 1974 (Public Law 93-523) has brought about a fundamental re-examination of the way water is handled before it is delivered to the customer. The U.S. Environmental Protection Agency (EPA), designated as responsible for establishing a program that will carry out the Act's provisions, is required to issue regulations, while state agencies are to develop water supply programs, and local governments to pursue these programs. Also, water utilities are required to monitor drinking water quality.

A primary feature of the Act is that economics must be considered before regulations are promulgated. An analysis of the regulations to be promulgated under the Act indicates that its economic effects will be minor on large water supply systems, but that there may be a potentially serious economic impact on small water supply systems due to the high unit costs generally associated with small treatment plants.

One option that might provide relief from this adverse economic impact is for a small system to join with other small systems or with a larger system to form a regional water supply. Presumably, the economies of scale associated with a regional system would benefit small system consumers. Historically, few tools and techniques have been available to assist water supply operators and planners in the analysis of these and related issues.

The effort described in this report has been specifically directed at the hydraulic and economic behavior of water distribution networks, through the development of data management, display and simulation modeling capability for a wide variety of issues involving such networks. A flexible approach which will aid in the analysis of water supply system problems has been devised, and implemented through development of a modular set of transportable computer programs.

This report is Volume I of a three-volume series that presents detailed information concerning development of the Water Supply Simulation Model (WSSM). The WSSM can be used to study some of the economic trade-offs associated with regional water supply systems, as well as many other important issues in water supply. The version of the WSSM described in this report was developed through a contract with W. E. Gates and Associates, Batavia, Ohio and Fairfax, Virginia (Contract No. 68-03-2941) and is an outgrowth of an earlier pilot implementation created by EPA's Drinking Water Research Division and the University of Cincinnati Computer Center.

TABLE OF CONTENTS

	Page
Disclaimer	i
Foreword	ii
Abstract	iii
Figures	vii
Acknowledgements	viii
Introduction	1
Water Supply Economics	2
Treatment Cost	3
Water Transportation Cost	4
Modeling the Water Supply System	5
Model Structure	12
File Structure	20
Software Modules	24
Establishment Module	25
Editor Module	26
Display Module	27
Lister Module	28
Hydraulic Analysis Module	28
System Solver Module	29
Case Study	36
The New Vienna System	36
Data Base Development	38
Delineation of System in Link-Node Form	40

TABLE OF CONTENTS (Contd)

Page

Determination of Physical System and Spatial Characteristics. . . 40

Development of Demand Data 42

Development of Cost Data 44

Example of WSSM Usage for New Vienna 45

Future Applications and Research 65

Data Base Management and Modeling 65

Spatial Analysis Concepts 67

Spatial Water Supply Modeling - Areas of Potential Application. . 70

Issues in Cost Allocation 71

System Dynamics 77

Summary and Conclusions 78

References 80

FIGURES

Number		Page
1	Cost Contour Map.	8
2	Subsidies for Residential Water Use Map	9
3	Subsidies for Industrial Water Use Map	10
4	Overall Structure of the WSSM	15
5	Node/Link Numbering Scheme	17
6	Record Structure for Files	19
7	Conventions for SOLVER	32
8	Method of Fixing Boundary Conditions at Nodes	35
9	Map of New Vienna	37
10	Schematic of New Vienna Water System	39
11	Link/Node Representation of New Vienna Water System . . .	41
12	Sample New Vienna Encoded Input Data	43
13	ESTBLINK, ESTBNODE Sample Output	50
14	Sample Output from ERCHECK	51
15	Sample Plot from NETPLOT	52
16	Sample Output from REPORTER	53
17	Sample Input/Output FIXL, FIXN, INSELK, INSEND	54
18	Sample WATINT Input and Output	58
19	Sample WATSIM Printed Output	60
20	Sample Card Deck Output of WATSIM	61
21	WATWSSM Sample Output	61
22	SOLVER Cost Mode Input and Output	63
23	Contour Plot of Unit Cost of Water Delivered to a Node. .	64
24	Model-Centered vs. Data-Centered Organization	68
25	Unit Cost Variation with Distance	76

TABLES

Number		Page
1	Link and Node Header Record Structures	21
2	Logical Link Record - Field Usage	22
3	Logical Node Record - Field Usage	23
4	New Vienna Water System O&M Costs	46
5	Node Cost Summary	47
6	Link Cost Summary	48
7	"Data Base" Requirements	66

ACKNOWLEDGEMENTS

Many people contributed to the development of the WSSM. Dr. Richard Stevie performed much of the early work on the original implementation of WSSM. Mr. A. Lee Cesario of the Denver Water Board, and Mr. Bruce Burbank of the Public Service Company of Colorado, provided advice, assistance, and access to their versions of the WATSIM hydraulic analysis model. Dr. M. Chandrashekar of the University of Waterloo, Ontario, graciously allowed the use of subroutines developed by him to be incorporated as the sparse matrix simultaneous equation solution techniques utilized in the System Solver module of the WSSM. The contributions of these individuals have been of significant benefit to the development of the WSSM.

The current version of the WSSM, as presented in this report, was developed by W. E. Gates and Associates, Batavia, Ohio, under Contract No. 68-03-2041. Dr. Richard Males served as principal investigator, Mr. Paul Wehrman performed much of the systems analysis and programming, and Dr. William Gates served as senior project advisor. Dr. Robert M. Clark served as project officer for USEPA.

INTRODUCTION

Passage of the Safe Drinking Water Act has intensified interest in problems related to water supply and water supply utility management. An economic analysis of the regulations to be promulgated under the Act indicates that there may be adverse effects on some water utilities.[1] This effect may be most pronounced in small utilities. An option often suggested is for small systems to combine or join with another larger system to form a regional water supply utility. The economies of scale associated with a regional water system would supposedly benefit small system consumers. There is nothing inherently wrong with regional approaches to water supply, however, there is a tendency on the part of Federal policy makers to interpret regionalization as being a centralized system with one large-scale plant. As pointed out by Angotti, "...the grant structure of the Environmental Protection Agency encourages a project approach which does in fact favor the single plant".[2] Although the Safe Drinking Water Act does not at this time contain grant provisions as does the Federal Water Pollution Control Act to which Angotti refers, Environmental Protection Agency (EPA) policy may still be interpreted as encouraging centralized systems.

Physically, it is possible to separate the water supply system into two components: (1) the treatment plant, and (2) the delivery (transmission and distribution) systems.[3] Each of these components has a different cost function. The unit costs associated with treatment facilities are usually assumed to decrease as the quantity of service provided increases. However, the delivery system is more directly affected by the characteristics of the area being served. The cost trade-offs between the two components will determine

the least-cost service area. As pointed out by Dajani and Gemmell "Economies of scale may be offset by diseconomies of dispersion, agglomeration, or spatial arrangement and pattern."[4]

Few instruments are available to study the economics of regional water supply systems. Therefore, EPA's Water Supply Research Division initiated a program to develop techniques and methodologies to allow for the evaluation of regional economic impacts for water supply. This is a report on the development of a simulation model that is designed to aid in such an evaluation. The model will also assist in providing insights into other water related economic issues such as spatial pricing and costing, conservation policies, user class subsidization, and fire protection capacity.

The model, called the Water Supply Simulation Model (WSSM), is the result of a joint effort by the U.S. Environmental Protection Agency and W. E. Gates and Associates. It incorporates a series of submodels to describe the various aspects of the economic, demographic, and hydraulic systems that make up a water utility. The logic utilized in developing the model is discussed in the following sections.

WATER SUPPLY ECONOMICS

A characteristic of many production and transportation problems is the tradeoff between the cost of building and operating facilities to meet demands for a product, and cost of transportation.[5] High transportation costs and low facility costs imply decentralization; the reverse implies a few large central facilities. These same characteristics must be considered in planning, designing, constructing and operating water supply systems.

Water supply systems are generally composed of (1) acquisition facilities, (2) treatment facilities, where needed, and (3) delivery systems.[6] Delivery can be further subdivided into transmission and distribution. Acquisition involves either tapping a source of water that is adequate in quantity to satisfy present and reasonable future demands on a continuous basis, or converting an intermittent source into a continuous supply by storing surplus water for use during periods of low flows. If the water is not of satisfactory quality at the point of acquisition, treatment plants purify it; that is, polluted water is disinfected, esthetically unattractive or unpalatable water is treated to make it attractive and palatable, water containing iron or manganese is subjected to deferrization or demanganization, corrosive water is stabilized chemically, and excessively hard water is softened. The delivery system, which constitutes the water transportation system and includes transmission and distribution components, conveys water to the consumers. Constructing and operating an urban water works system involves large investments in both operating and capital funds. The economics of the treatment/acquisition component and the transportation/distribution component are discussed in the following sections.

TREATMENT COST

The two main elements that comprise treatment cost are construction or capital cost, and operating and maintenance cost. A number of investigators have examined treatment costs in an attempt to explore the relationship between cost and the design capacity or output of the plant. Typical of these relationships is the following:[7]

$$TC = EQ_n^e \quad (1)$$

where

TC = total capital cost of a complete water treatment plant in dollars

Q_n = the design capacity of the plant in millions of gallons per day (MGD)

E = constant

e = elasticity of total cost with respect to design capacity (with economies of scale $e < 1$)

Dividing both sides of (1) by Q_n yields:

$$C_u = EQ_n^{e-1} \quad (2)$$

where

C_u = unit capital cost in dollars per million gallons

If $e - 1 < 0$, then (2) indicates declining unit costs with increased plant capacity, which suggests the existence of economies of scale.

Similar relationships have been developed for operating and maintenance costs.

WATER TRANSPORTATION COST

Water is transported and delivered to consumers through transmission pipelines and distribution mains. Transmission pipelines are the major trunk lines used to transport large volumes of water. They connect the treatment plant to the pumping station and, if gravity tunnels are not used, to the distribution system. Pumping stations, pipelines, labor and energy comprise the major costs of transmission. The distribution works include the meters, pipelines, and storage facilities (water tanks) necessary to convey the water from the transmission system to the consumer. A pumping station might also be involved if ground storage exists. Therefore, distribution systems include the operating and capital costs of pipelines, water towers, and pumping stations.

Several investigators have attempted to analyze the transportation costs associated with water supply. Coase, in his article on uniform pricing systems, examines the shape of the supply and cost curves when the same price is charged for a product or service over a given area, even though the supply cost may vary from one part of the area to another.[8] He argues that the marginal costs of supply to each consumer rise with an increase in distance from the plant and that the marginal costs of supply to each individual consumer are constant at a given distance from the production source. As a result, the shape of the cost curve depends upon the quantity consumed by individuals at various distances from the plant.

Ford and Warford estimated water supply costs using Area (in square miles) and Q (daily water supply) divided by Area.[9] They found economies of scale when Q/Area increases, but diseconomies when Area alone increases.

Linaweaver and Clark provided an engineering and economic basis for examining transmission costs of water.[10] Two components were incorporated: capital cost of pipe and energy cost for pumping water. The energy cost depended upon the flow and distance pumped when capital cost was determined by pipe length alone.

MODELING THE WATER SUPPLY SYSTEM

The concept of two components, acquistion/treatment (A-T) and transmission-distribution (T-D) was maintained for purposes of model development. In addition the concept of a water utility as a network overlaid upon a spatial distribution of supply and demand was introduced. The model explicitly deals with the relationship of delivered water costs to the service requirements of spatially distributed demand. This spatial representation is based on a characterization of the water supply system as a link-node network.

For purposes of model development, it was assumed that water enters and leaves the system only at nodes, which represent treatment plants, junctions, demand locations, and storage tanks. Water is carried between and among nodes through links or pipes connecting them. It is assumed that there is no water loss in a link, and that the flow-head loss relationship is known for a given link. This form of representation is in general a simplification and an aggregation of the real network - typically, only major pipe elements are included, and withdrawals are "lumped" at the nodes, rather than being distributed along a pipe.

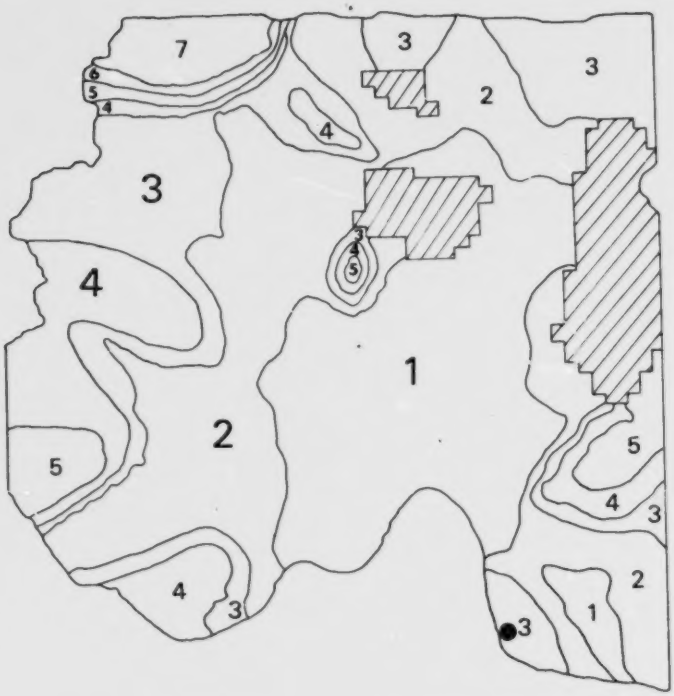
This form of representation of the physical system is quite common in technical analysis of water distribution systems. From an economic standpoint, however, another form of categorization is that mentioned earlier between acquisition/treatment (A-T) elements and functions, and transmission/distribution (T-D) elements and functions. In this study, A-T costs are all of those costs associated with getting water into the network, and are considered to be identified with the node at which water enters the network. Thus, costs of treatment plant works, chemicals, purchased water, etc. are associated with the supply nodes of the system. T-D costs are those related to delivery of the water to customers, and to provision of storage for peak/off-peak usage and fire protection. Both A-T and T-D have an operation and maintenance, and a capital cost, component. In addition, operation of a water supply system contains a general overhead component which is not directly associated with a particular hydraulic element.

The primary objective of the Water Supply Simulation Model (WSSM) development efforts has been to provide a tool that can estimate the actual cost of delivery of water to a particular user. This approach represents a change from traditional costing approaches. In general, water supply systems have

not been analyzed in this fashion, but rather in terms of costs to classes of users, and revenues to be obtained from these classes of users. When considering issues such as consolidation and regionalization, however, the cost of serving particular locations becomes important in examining the overall economic behavior of the system. The combination of link-node and an A-T/T-D form of representation is an important feature of the WSSM. By associating A-T costs with supply nodes, and T-D costs with other physical elements, it is possible to "trace" the flow of water through the system from source to user, and allow the water to "accumulate" costs based on the elements it uses. Thus, if in a particular region of the distribution system all water flowing to a particular zone must pass through a pump, then that water "acquires" the cost of that pump. The other portions of the network, which do not receive the benefit of the pump (insofar as there is no "local" water flowing through it) are not "charged" to the pump.

The A-T system is, as was noted previously, essentially a centralized one - but this is perhaps more due to historical public health reasons than to strict economic ones - obviously, other options for A-T (e.g. cisterns) are possible, and at some point T-D costs from a centralized A-T site are such that it is preferable to develop A-T sources closer to the ultimate user. In general, sizing decisions for A-T elements must be made for a timeframe other than that for T-D elements.

The consequences of these assumptions are illustrated by Figure 1. Figure 1 is a contour map of costs, derived from model runs on a water supply system data base showing zoned costs for delivery of water in the system. Displays such as this one can easily synthesize the results of complex physical, policy and economic situations. The water treatment plant is located as marked in the lower right hand corner of the service area. As can be seen, costs rise rapidly toward the suburban areas in the northwest. Figures 2 and 3 are maps showing subsidies (excess of costs over revenues) throughout the service area by location,



ZONE	COST ($/1000 GAL)*
1	.15 – .20
2	.20 – .29
3	.29 – .38
4	.38 – .47
5	.47 – .57
6	.57 – .66
7	.66 – .76

*1973 COSTS

●- Treatment Plant

Figure 1: Cost contours for Cincinnati Water Works area, based upon Water Supply Simulation Model.

Reference: Goddard, H.C., Stevie, R.G., Trygg, G.D., "Planning Water Supply: Cost-rate differentials and Plumbing Permits", EPA 600/5-78-008, May, 1978, Cincinnati, Ohio

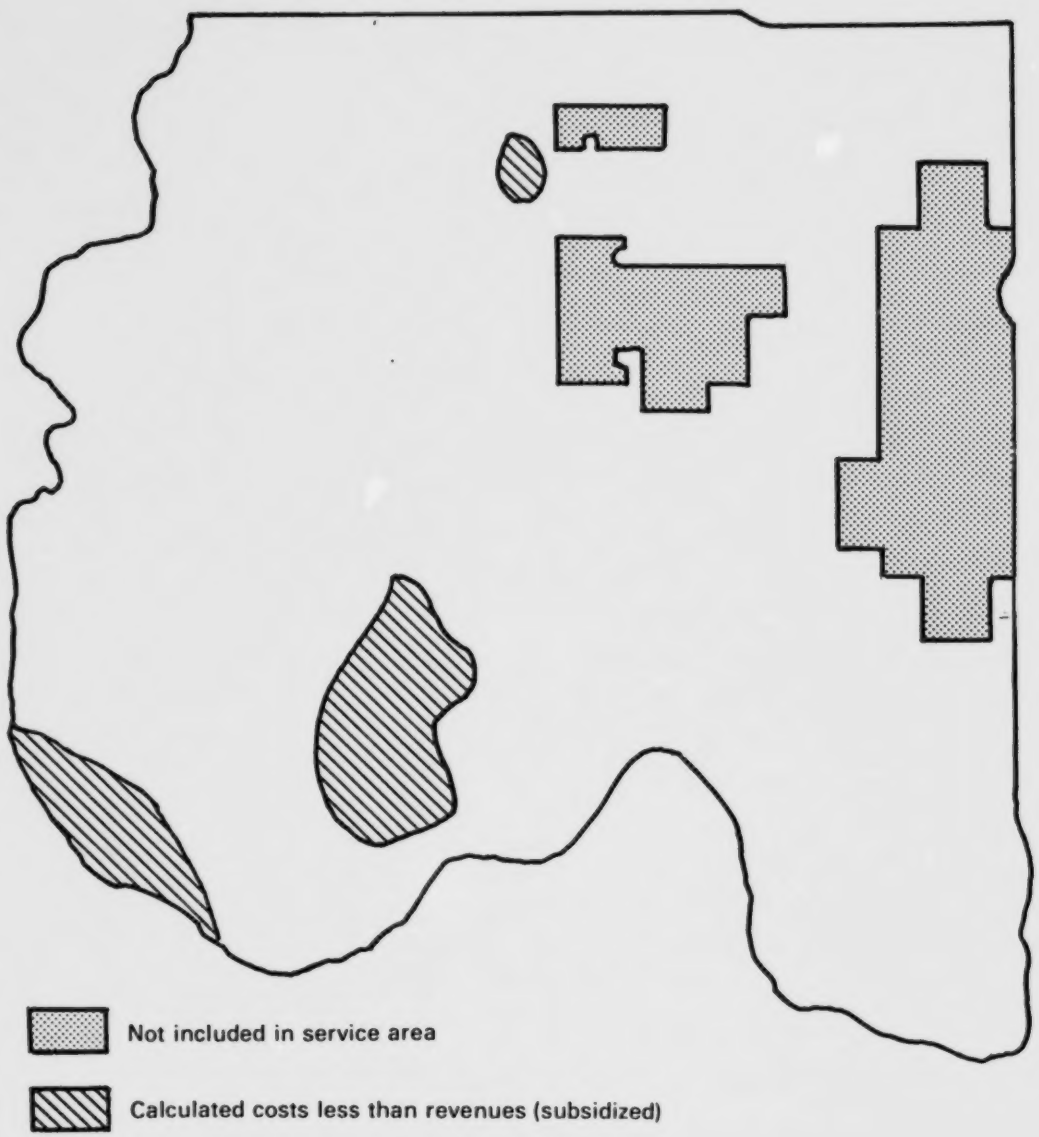


Figure 2: Areas being subsidized for residential rates, Cincinnati Water System, based on Water Supply Simulation Model

Reference: Goddard, H.C., Stevie, R.G., Trygg, G.D., "Planning Water Supply: Cost-rate differentials and Plumbing Permits", EPA 600/5-78-008, May 1978

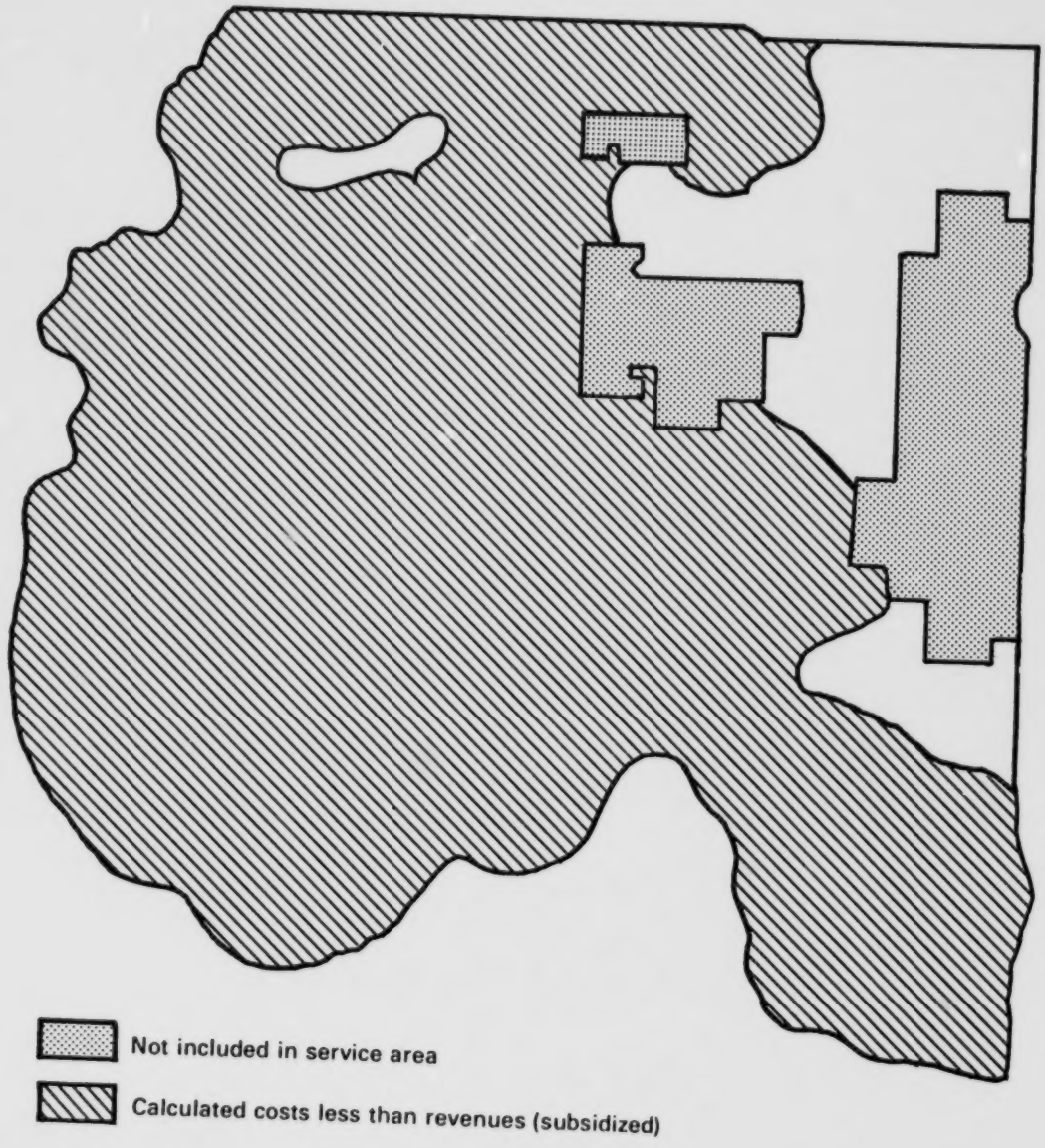


Figure 3: Areas subsidized for industrial rates, Cincinnati Water System, based on Water Supply Simulation Model

Reference: Goddard, H.C., Stevie, R.G., Trygg, G.D., "Planning Water Supply: Cost-rate differentials and Plumbing Permits", EPA 600/5/78-008, May, 1978, Cincinnati, Ohio

for residential and industrial peak usage situations. These results are from an early implementation of the WSSM, and, while not to be taken as precise indications, do show the strength of the approach, and the character of questions that can be raised.

The approach discussed thus attempts to assign costs to beneficiaries - the above analysis shows how this can be done in terms of location of beneficiaries. A further extension would be to assign costs in terms of the time-based demand of the water users. Water demand typically goes through both a seasonal cycle and a daily cycle. Storage elements of a water supply system that exist either prior to, or as a portion of, the A-T element, may be extensive and significant in cost, and would be associated primarily with seasonal storage and protection of the ability of the water supply to continue delivery at times when the treatment plant is shut down. Storage associated with the T-D component provides load smoothing in daily operation, maintains zonal pressures, and also allows for conformance with fire codes. The maintenance of pressure and the provision of fire protection are benefits that are typically unaccounted for in cost allocation analyses, which are frequently based on measures of consumptive use.

The Water Supply Simulation Model is a tool in the analysis of such complex cost allocation problems. The overall water supply system is represented by links and nodes, that are defined physically, spatially, and in terms of costs. Different "scenarios", representing differing conditions of demand, or structures of the hydraulic elements, can be specified and stored simultaneously within the WSSM. Each scenario can then be analyzed in terms of its impact on flows and pressures within the system. The resulting flow pattern can then be used to "trace" water through the system, and associate costs with it, leading to a delivered cost of water at a node. Many scenarios

can be run, with the results stored in the data base for comparison, display, and reporting. The WSSM departs from previous work in a number of ways:

- it is designed to provide both hydraulic analysis and economic analysis
- it operates in a "data base" format, as opposed to a mathematical model format
- it is open-ended and flexible - a set of basic tools, that encourages and allows the user to develop and use additional modules to perform special-purpose analyses.

The WSSM will be useful because it provides both a tool for analysis, and simultaneously a technical context for discussion of the complex time-based, spatial economic problems associated with water supply systems.

MODEL STRUCTURE

The following basic concepts underlie development of the WSSM:

- spatial analysis - the spatial location and inter-connection of the water distribution system, and its relationship to other geographic parameters (terrain, soils, population, service zones, etc.) is explicitly specified, stored, and used, both in analysis and display.
- data base management - information relative to the water distribution system is stored in a flexible, general-purpose data base that serves as a central warehouse of data readily available to be used in analysis procedures of various kinds, or for display;
- mathematical modeling - modular mathematical models extract information from the data base, operate upon it, and store the results back into the data base, for display or further analysis by other models.
- graphical display - one of the major drawbacks of previous analytical tools for water distribution systems was the inability to easily comprehend the large amount of data generated by the mathematical models. The WSSM contains a variety of graphical display options, to ease the interpretation of computer generated data through mapping.

In order to achieve these objectives a protocol for reducing the physical and economic elements of a water supply system to data amenable to mathematical analysis has been established. The system is described as a network of pipes, storage tanks, treatment plants, demands and other hydraulic elements. Information concerning the network is stored in a network data base, which also provides the capacity to maintain additional descriptive or calculated information about each element, such as size of pipe, geographic location of each demand, population associated with a demand, connectivity of pipes, etc. Certain basic information must be stored, in order for the system to operate, but other information is elective, and is a function of the particular uses and analysis to which the WSSM is to be put. Other program modules communicate with the data base through the standardized data base access methods, which consist of routines to extract or insert information into the network data base. The Hydraulic Network Analysis Module provides a solution of the network, i.e. given demands and pipe sizes, the flow and pressure throughout the network are defined (as in the well-known Hardy Cross method). The Data Base Establishment and Edit Modules provide the capability to create a new network description for a particular area, or to modify an existing one. Error checking capacity is included in this module. Other physical or economic models similarly operate upon the data base to calculate parameters such as time of travel from a particular water source to a demand, or for cost allocation. The information so calculated is re-inserted in the data base. General purpose display and reporting modules then allow any of the stored data to be displayed in a variety of forms, such as tabular or graphic output. By adhering to such a structure for the WSSM, new modules can easily be added at any time. The model can be used for estimating various economic features of the system

and in supporting theoretical studies of the optimal size of regional distribution systems.

Figure 4 illustrates the way in which the WSSM operates. Data is entered into the data base (Link and Node files) through an establishment module. Once the data base is established various program modules manipulate it. The general elements of WSSM are listed below.

Network Data Base:

- separate but cross-referenced data files for the link (pipe) elements and nodal (demand, source, etc.) elements of the network;
- standard and user-specified data items.

Data Base Access Methods:

- routines designed for efficiency and ease of use;
- routines in standard Fortran, not strongly tied to a particular computer.

Hydraulic Network Analysis Models:

- non-proprietary WATSIM model, with both steady-state and dynamic simulation capabilities (although WSSM makes use of the steady state capacity only at this time), and ability to model a wide range of hydraulic elements (tanks, parabolic pumps, check valves, pressure regulating valves, booster pumps).

Other Physical/Economic Models:

- linear cost allocation procedure;
- general purpose "physical system solver" to solve problems involving multiple sources, travel time, and mixing at nodes.

Display and Reporting:

- general purpose listing programs for both link and nodal elements;
- flexible pen plotter display program, with capability of producing annotated maps of network.

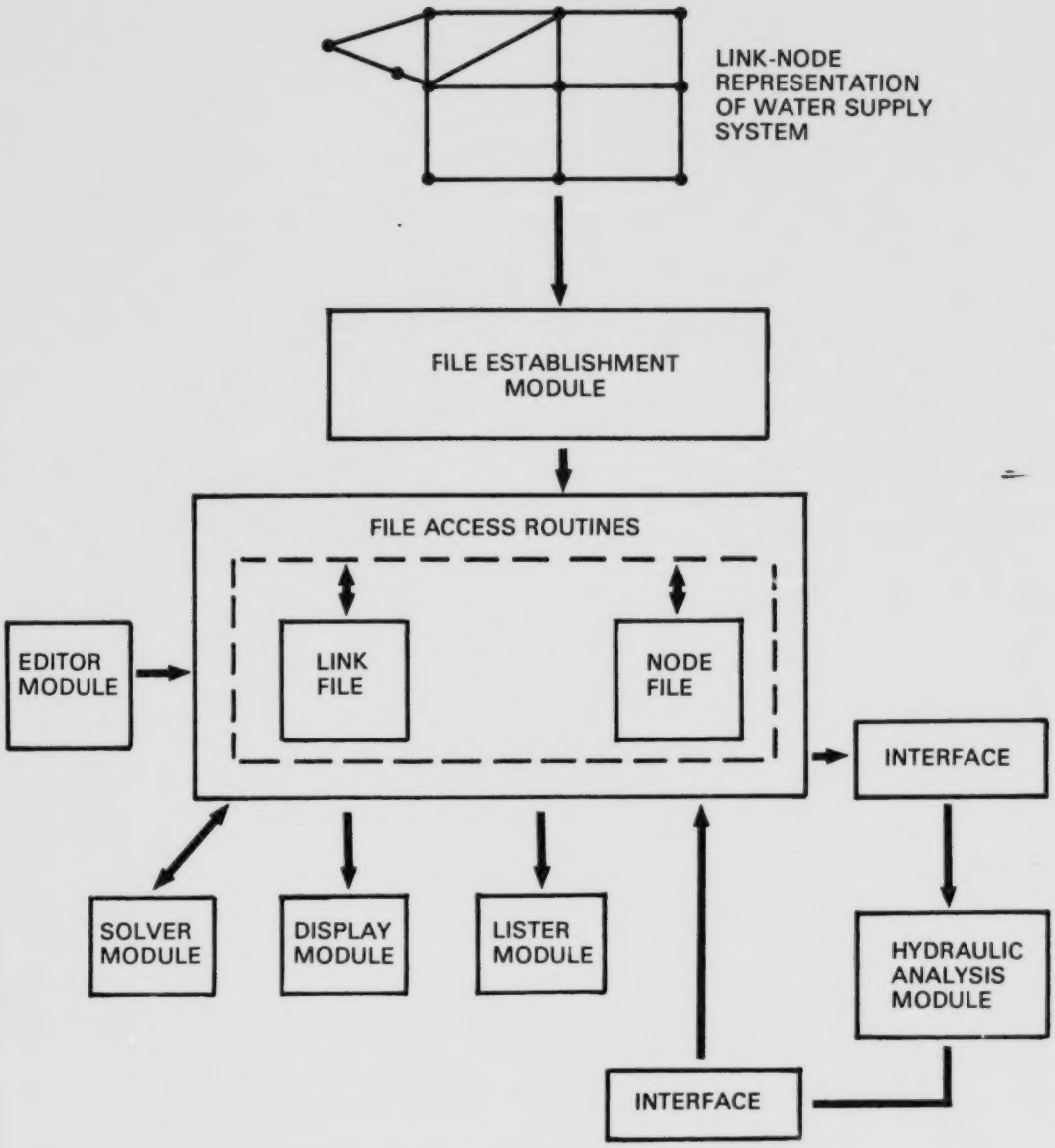


Figure 4: Basic structure of the water supply simulation model.

Data Base Establishment and Edit:

- establish comprehensive set of link and node files and edit programs with extensive checking and cross-referencing of information between the two files, in order to maintain the topological integrity of the network.

The original concepts and approaches of the model were tested in a pilot study of the Cincinnati, Ohio, Water Works system, leading to a revised, more general-purpose version, using New Vienna, Ohio, and Kenton County, Kentucky and Tampa, Florida water systems as "test-beds". The New Vienna example is described in detail in a later section of this report, and additional testing, verification, and installation of additional features is currently being carried out for the Kenton County and Tampa systems.

In the following sections the creation and structure of the data base are discussed . The individual program modules used to establish and manipulate the data base are described and an example of the creation of a case study is presented.

As a data base management system, the WSSM utilizes files that are permanently stored, as opposed to "decks" of data cards. The system is thus characterized by its file structures (what files exist, and how they are organized), its record structure (how files are organized into separate components describing items of interest), and the fields within each record (what specific data elements are contained for each item of interest). For the WSSM, the primary items of interest are the nodes and links of the distribution system. Two files are maintained - the node file, containing records for each node, and the link file, containing records for each link. The nodes and links define the network and each node and link is numbered as shown in Figure 5. The individual node and link numbers (identifiers, "ID's") correspond to individual records in the link and node files; the records contain descriptive data

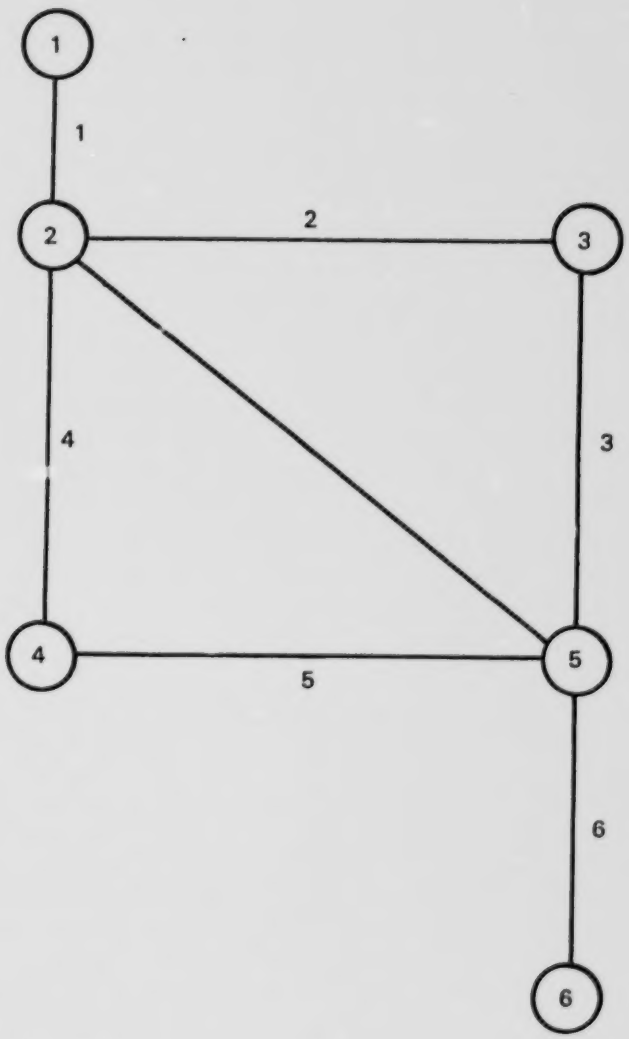


Figure 5: Node/Link numbering scheme.

about the corresponding link or node. Each record in a file is structured in the same general fashion, as shown in Figure 6.

The individual data elements (fields) describing each node or link are characterized as one of the following types:

- geographic - where the link/node is located
- topologic - how the link is connected to nodes, or what nodes terminate each link and what links stem from each node
- attribute data - descriptions of information pertaining to each link/node e.g., diameter of pipe for a link, magnitude and type of demand for a node, etc.
- working storage and "user-definable" fields - additional "free" space set aside to store other attribute data, as necessary for a given study.

In order to accomplish this structure, each node, and each link, is given a unique numeric identifier, starting at 1 and continuing to the maximum number of links/nodes in the system. Thus, there will be both a link number 25 and a node number 25, but there is no possibility of confusion, as the information is stored in the separate link and node files.

The WSSM link and node files are direct access files, meaning that information can be obtained about each node or link simply by knowing the node or link number, without having to search through all the other nodes/links, as in the case of files that are organized sequentially. Direct access file organization is inherently more powerful than sequential organization, but does exact a certain price in terms of storage use and cost of access - for the relatively small files expected to be used in the WSSM, these factors are likely to be unimportant, and the power of the direct access capability is clearly to be preferred. In any case, the structure of the node/link files and associated access routines has been designed to minimize cost of storage and processing. The file structure within these files is described in the following section.

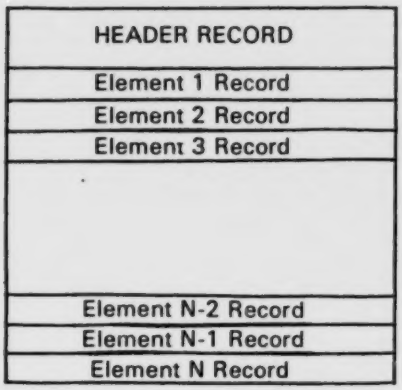


Figure 6a: File structure for link and node file of N elements.

Element Number	Topological Connectivity Data Fields	Spatial Coordinate Data Fields	Attribute Data Fields	User Working Storage
	(Cross-reference pointers between link and node files)	(Location of node or ends of link)	(Size, type, material, demand, etc.)	

Figure 6b: Record structure for an individual link or node element.

Figure 6: File and record structure.

FILE STRUCTURE

The link and node files are interrelated, and taken together, constitute a description of the topology, location and data attributes of the modeled water system. Certain information is stored redundantly in both files for ease of programming. The file structures for the node and link files are similar in character. Each file consists of a header record followed by up to 79 physical records containing ten logical records each. A "physical" record is the actual amount of information handled by the computer as it transfers data back and forth from disk storage to memory. To minimize the number of these data transfers, logical records, containing the information associated with each link or node, are combined, ten at a time, into physical records. This technique, called "blocking" is commonly used in computer systems. The maximum number of links or nodes modeled by this system is then 790. The maximum of 790 was selected arbitrarily to handle existing case studies. It should be noted that the number of physical records in each file can be modified at the time the system is installed. The physical record length for the link file is 400 four-byte words, while the physical record length for the node file is 600 words. Thus, the header record for the link file is 400 words. For the node file, the header record is 600 words, and each logical record is 60 words. Each logical record in the link file corresponds to a link in the network, and each logical record in the node file corresponds to a node in the network. A detailed description of the file structure is contained in Volume III.

The information stored in the link and node header records is shown in Table 1. This information contains global attributes, and other information pertinent to the efficient execution of the system. The information stored on the individual link and node records is shown in Tables 2 and 3. As can be

seen from the tables, several field positions of the logical records are reserved for certain types of "protected" data. Except for the establishment and editing modules, all other software with file writing capabilities is designed to prevent destruction of these reserved fields.

TABLE 1. LINK AND NODE HEADER RECORD

File Type	Field	Description
Link	1	Highest legal record number
	2-3	Date/time file established
	4-5	Date/time of last update by programs FIXL or FIXN
	10	Highest currently used Link Logical Record number
	11	Code for last program that modified the file.
	12	Number of physical records in file.
Node	1	Highest legal record number
	2-3	Date/time file established
	4-5	Date and time of last execution of FIXN, FIXL, ESTBNODE, or ESTBLINK
	6-9	Bounding rectangle coordinates: Y maximum - north (ft) Y minimum - south (ft) X maximum - east (ft) X minimum - west (ft)
	10	Highest currently used node logical record number
	11	Code for last program that modified file
	12	Number of physical records in file

All other fields - currently unused, but reserved for global and zonal summary data.

TABLE 2. LOGICAL LINK RECORD - FIELD USAGE

Field	Field Usage
** 1	ID (Link identifying number)
** 2	Link Type
** 3	Zone 1 (Primary Zone Identifier)
4	Zone 2 (Secondary Zone Identifier)
** 5	Upstream Node
** 6	Downstream Node
** 7	X Coordinate of upstream node
** 8	Y Coordinate of upstream node
** 9	Z Elevation of upstream node
** 10	X Coordinate of upstream node
** 11	Y Coordinate of downstream node
** 12	Z Elevation of downstream node
13	Diameter (inches)
** 14	length (feet)
15	Date of installation or replacement
16	Cost factors
21	Frictional coefficient
22/40	Model specific attributes/work storage

** Reserved written to only by ESTABLISHMENT MODULE and routines FIXL and FIXN

TABLE 3. LOGICAL NODE RECORD - FIELD USAGE

Field	Field Usage
** 1	ID (Node Identifying Number)
** 2	Node Type
** 3	Zone 1 (Primary Zone Identifier)
* 4	Zone 2 (Secondary Zone Identifier)
** 5	X Coordinate of Node (feet)
** 6	Y coordinate of Node (feet)
** 7	Z Elevation
** 8/17	Attached links
18/60	Nodal-specific attributes (cost, demand, etc.)/ working storage

** Reserved written to only by ESTABLISHMENT MODULE and routines FIXL and FIXN

SOFTWARE MODULES

In view of the wide variety of hardware on which the WSSM may operate, no attempt was made to provide a complete "turnkey" system. Rather, the basic elements are provided, and the interaction of these elements, and the structuring of the files are described. It is the responsibility of the particular user at an installation to handle the "job control language" (interaction with the computer's operating system) necessary to assemble the programs and files in an operational manner for a given application. No other form of support to assure transportability could be devloped within the scope of the research project.

All software modules of WSSM are written in Fortran IV, adhering as closely as possible to ANSI Standard Fortran IV; this increases the ease with which WSSM can be transported from one computer to another. However, it is recognized that there may be hardware environments in which the system will require modifications. This problem has been minimized and localized by

- separating the file access routines into a separate module
- preparing careful internal documentation of those parts of the code which are more susceptible to specific computer dependency.

The seven software modules described herein are: the establishment module; the editing module; the display module; the listing module; the hydraulic module; the system solver module; and the I/O module. Example outputs are presented later in this report.

The establishment of a data base for WSSM requires the use of four of these modules. The establishment module prepares a list of possible errors for the user while creating the files; no corrections of the input data are made. The display and listing modules are then used to verify the contents of

the files, and necessary corrections are made with the editing module. Because of the importance of the integrity of the topological and geographic information in the files, all modules except key establishment and editing modules are designed to preclude destruction or distortion of this data.

ESTABLISHMENT MODULE

This module consists of four separate programs: ESTBNODE; ESTBLINK; ERCHECK; and SCANCOL. The first two programs initialize the node and link files, set "background values" for unused fields to -9999, and store the primary information of the system. The other two programs perform error checking, providing as output a list of potential errors within the data file.

ESTBNODE establishes the node file on disk. This program reads a deck of nodal information cards, one card per node, and stores the information in the file. Data presented on the node card are: node number, node type, service zone, easting, northing, elevation, and other attributes, depending on nodal type. Printer output from this program consists of an echo print of the input card and a list of error messages for data that is outside of the acceptable limits.

ESTBLINK establishes the link file. Input consists of a deck of link cards, one card for each link record to be established. The data accepted by the program on each card are: link number, upstream node number, downstream node numbers, type, service zone, diameter, and roughness coefficient. The "upstream/downstream" node defines the convention for positive/negative flow in a link. Flow is upstream to downstream. ESTBLINK accesses the node file to retrieve the geographic information to be stored in the link record that is being established and to store topologic information in the node file. Printer output from ESTBLINK contains both an echo print of the input cards and a list of error messages.

ERCHECK is the routine which reads through both files and searches for possible topological errors within the network. Output from this routine is a list of messages pertaining to isolated nodes or links, links connected to non-existent nodes, parallel pipes, disagreement concerning coordinate data, and a list of network ends with their corresponding types.

SCANCOL is a routine that reads through the files searching for out of range data. Input to SCANCOL consists of a single control card which contains: file selection code, search codes, search column, maximum acceptable value; and minimum acceptable value. This program is able to access either file and to search by: 1) service zone, 2) type, and 3) the entire file. Program output is a list of the record numbers and corresponding values that are out of range. SCANCOL may be used as both an error-checking program, and in applications mode, to create exception reports.

EDITOR MODULE

This module consists of four separate programs: FIXL, FIXN, INSELK, and INSEND. The first two programs are designed to correct topologic and geographic data within the files; the other two are simple attribute insertion routines. FIXL and FIXN are the only programs in this module with the capacity to modify geographic and topologic data. These two programs update existing records, and add and delete logical records from the file. FIXL and FIXN modify both files so that the geographic and topologic information in each of the files is consistent. INSEND and INSELK are designed to correct or insert attribute data into the files. The geographic and topologic information cannot be modified by these routines. These two routines provide the user with an efficient means of attribute insertion for nodes and links. Input to

INSELK and INSEND consists of an initial control card and a series of attribute insertion cards. The control card provides for insertion by zone or type; otherwise, insertion will take place by specified records on the attribute insertion cards.

DISPLAY MODULE

This module consists of a single program, NETPLOT. NETPLOT is a general network plotting utility capable of a variety of different displays. The type of display generated is controlled by the information contained on the input cards. Four input cards are required per plot request, with multiple plot requests allowable per execution of the program. The four plot description cards are:

Card 1 - the window and scale selection card;

Card 2 - the option selection card;

Card 3 - the node symbol selection card; and

Card 4 - the plot title card

On Card 1, the user specifies plot scale and paper length, (with paper length overriding scale if the two are in conflict) and the "window" to be plotted if the entire network is not desired. On Card 2, the user may elect to: place a box around the plot; provide an overlay grid; choose to plot only the nodes; represent the link with a line or arrow; plot numeric identifiers, and record attributes; or plot by specified attribute (i.e., sewer zone, pipe size, etc.). On Card 3, symbology for the node types can be defined for the plot. On Card 4, the user specifies the title to be plotted on the plot's title box. NETPLOT also writes a series of messages to the printer.

NETPLOT uses plotting subroutines in industry-standard ("CALCOMP") format, which must be available at the host installation.

LISTER MODULE

This module consists of a single flexible report generating program, REPORTER. The type of report and format are controlled by a series of input cards that determine the file (node or link), the parameter fields to be reported and the selecting criterion to be applied to records included in the report. The program keeps track of the pages generated, and prints a heading at the top of each page. REPORTER has the capability of listing the information in either a column or row format by the choice of modes of operation; with row selection, a maximum of ten attributes can be listed at a time. REPORTER is able to list information from either the node or link file, but not from both simultaneously.

HYDRAULIC ANALYSIS MODULE

The Hydraulic Analysis Module consists of the program WATSIM and associated interface routines to the node and link data files. WATSIM is a public domain program, originally developed by Science Application, Inc., in work sponsored by the Office of Water Research and Technology, U.S. Department of Interior. WATSIM is a powerful program capable of steady-state and dynamic simulation, and also capable of handling a wide variety of hydraulic elements, including booster pumps, check valves, and pressure regulating valves. The version of WATSIM utilized in WSSM is an IBM Fortran modification of the orginial Univac code, developed by Public Service of Colorado, Inc. The IBM Fortran code is more easily transportable than the original Univac Fortran, and the program conforms generally to the originally published documentation for WATSIM.[11] WATSIM was selected because of its ready availability, because it is one of the most widely used public domain hydraulic network analysis programs, and

because its basic solution method (node-oriented Newton-Raphson iteration using sparse matrix techniques) is similar to that of WATER, the hydraulic analysis model used in the early development phases of WSSM.[12] Minor modifications to WATSIM associated with the interface to WSSM, have been made in this study.

The interface component of the hydraulic analysis module feeds data from the node/link data base into the card-image input format normally used by WATSIM. A special-purpose routine, added to the WATSIM code, places the results of the hydraulic analysis in a data file that can be inserted (under user control) back into the data base. All normal WATSIM output continues to be provided. It should be noted, however, that the interfaces, as currently designed within WSSM, are capable of operating only in the steady-state mode, although the verison of WATSIM supplied with WSSM does contain dynamic simulation capacity, and could be used in a stand-alone (free of WSSM) mode if dynamic simulation is desired. By selecting the input interface that simulates normal WATSIM operation in steady-state mode, and by adding an output routine as the outgoing interface, all the original power of WATSIM is preserved, and the method of interfacing is made clear, should users desire to substitute other hydraulic analysis techniques.

SYSTEM SOLVER MODULE

This module consists of a single routine, SOLVER, designed to solve a system of simultaneous linear nodal equations. Three basic types of problems of interest in analysis of water distribution networks can be formulated as simultaneous linear equations. Each type requires that a steady-state solution of the hydraulics of the network has been developed and stored in the data base, thus defining velocity and flow in each link. The travel-time problem

determines the flow-weighted average time of travel to a node in the network. Time-of-travel information can be used in studies of trihalomethane generation, water-borne disease, etc. The concentration problem determines the concentration of constituents at a node, when the network is supplied from multiple sources having differing qualities. Conceptually, for a two source network, in which the water from one source is dyed blue and the water from the other source is dyed red, the system solver module will determine the "color" at any intermediate node in the network.

The third type of problem, that of cost assignment at a node, is handled through a linear cost allocation model. Under this model, the system solver formulation is used to determine delivered unit costs of water to each node, based on an assumed hydraulic flow pattern, and defined annualized element costs for links, nodes, and acquisition/treatment at sources.

The solution method is straightforward, and makes use of sparse matrix techniques to conserve computer space. The solution at a node can be inserted, under user control, back into the data base. Thus, for example, different hydraulic patterns could be used, and a set of different travel times or cost allocations stored in the data base of each node, and then compared in report or display software.

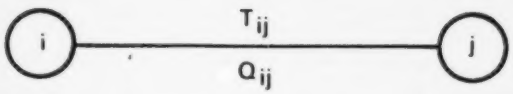
Formulation of the System Solver Equations

Each of the three types of solutions assumes complete mixing at nodes, and operates on a flow-weighted average basis. In essence, it is assumed that the characteristic of the water at an upstream node is carried along to a downstream node, where it is mixed with all other water influent to the node. The water leaving the nodes thus has the flow-weighted average characteristic of the water that has entered and mixed at the node. Referring to a single

link element between nodes i and j (Figure 7), the flow is Q_{ij}. By convention, flow into a node is positive, flow out of a node is negative. Thus a positive Q_{ij} implies flow into node i from node j. The unknown characteristics (concentration, time of travel, unit cost of delivered water) at each node are C_i and C_j, at nodes i and j respectively. The travel time type of solution incorporates a transform of the characteristic between node i and node j - thus, the travel time T_{ij} for a link ($length_{ij}$/velocity in link ij), is a quantity that can be calculated for a given hydraulic scenario and then stored in the data base. The travel time of water leaving node j when it arrives at node i is simply C_j+T_{ij}, that is, the travel time at the source node, plus the travel time in the pipe. Similarly, for the cost solution, a link-related cost must be added to water flowing between nodes.

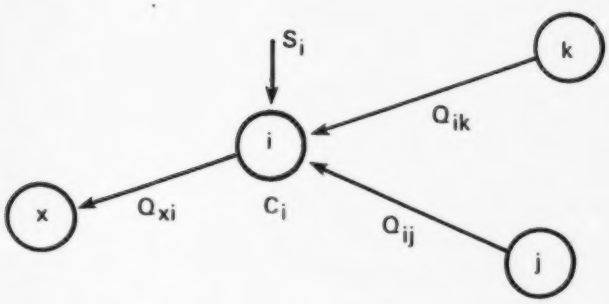
At a node, the quantity of water entering the node from other pipes in the network is simply $\sum Q_{ij}$, where the sum is over all pipes emanating from nodes j that carry water <u>into</u> node i (i.e. Q_{ij} is positive). In addition, the node may receive water from a source external to the network. This supplied water is designated as S_i, and it has associated with it a characteristic value SC_i. Note that very few nodes in the network will generally receive water from an external source. The characteristic SC_i associated with this external water may be a concentration of a pollutant, an "age", a unit cost, etc. depending upon the type of solution being considered.

For cost allocation type solutions, the cost of a node itself is assigned to water at the node, e.g. the cost of a tank in the system must be added in to the cost of water passing through the tank, on a flow-weighted basis. This incremental nodal cost at each node (which is fixed, and stored in the data base, and is <u>not</u> a function of flow at the node) is designated as N_i.



Q_{ij} = flow into i from j = $-Q_{ji}$
Tij = travel time from i to j along link ij
= length of link ij / velocity in link ij

Figure 7a: Conventions for a link.



C_i = characteristic value (e.g. concentration) at node i
S_i = quantity of external input flow at node i
SC_i = characteristic value associated with water influent at Si

By mass balance:

$$Qxi = S_i + Q_{ik} + Q_{ij}$$

$$Ci = \frac{Q_{ik}\, C_k + Q_{ij}\, C_j + S_i\, SC_i}{S_i + Q_{ik} + Q_{ij}}$$

(Complete mixing, flow-weighted average, concentration solution)

Figure 7b: Conventions for a node and concentration - type equation.

Figure 7: Conventions for solver.

Thus, while each of the three solution types is characterized by a constituent balance and flow-weighted averaging at each node, the time of travel type of solution must add in a pipe-related L_{ij} component, the cost type solution must add in a node-related N_i component as well, and the concentration solution has neither the N_i nor the L_{ij} component.

Writing a constituent balance at node i, using the above terminology, for the concentration type of solution we have:

$$C_i = ([\textstyle\sum Q_{ij}] + S_i SC_i)/([\textstyle\sum Q_{ij}) + S_i] \quad (3)$$

For the travel time solution:

$$C_i = [(\textstyle\sum (Q_{ji}C_j + L_{ij})] + S_i SC_i)/[\textstyle\sum Q_{ij} + S_i] \quad (4)$$

and for the cost type solution:

$$C_i = (\textstyle\sum (Q_{ij}C_j + L_{ij})] + N_i + S_i SC_i)/[\textstyle\sum Q_{ij}) + S_i] \quad (5)$$

where

C_i = characteristic value associated with node i

Q_{ij} = flow from j to i

L_{ij} = characteristic value associated with link i, j (cost, travel time)

S_i = external supply at node i

SC_i = characteristic value associated with external supply at node i (unit cost, age, concentration)

N_i = nodal cost value at node i

In general

$$C_i = \left[\frac{\sum_j Q_{ij} C_j + S_i L_{ij} + \delta_2 N_i + S_i SC_i}{\left(\sum_j Q_{ij} \right) + S_i} \right] \qquad (6)$$

where

S_i = 0 for the concentration case

1 for the cost and travel time case

δ_2 = 0 for the concentration and travel time case

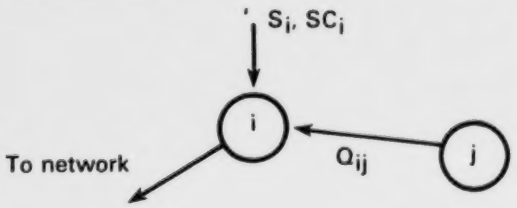
1 for the cost case

Thus, there are n equations that can be written at each of the n nodes. The equations are linear in the unknown, C_i, and can be solved by standard techniques.

In the actual implementation of SOLVER, there is a slight difference in the manner in which the S_i and SC_i terms are handled from that given in the above formulation. Instead of using the value of SC_i as a boundary condition, the value of the constituent, C_i, is fixed for nodes that have external supplies, to the value SC_i. That is, it is assumed that there is no mixing at these nodes. As flow will in general be away from such source nodes, this is not a major constraint. This is simpler to program, and requires less input data. If nodes that have external supply (such as treatment plants, pumps, or tanks) are connected into the pipe network by a single link, as shown in Figure 8, then fixing the value of C_i at such a node is equivalent to the above formulation, but, as noted above, is easier to formulate. Most hydraulic network systems are naturally structured in this manner (with supply nodes entering into the network at a single link), so there is no major problem in using the SOLVER algorithim.

SOLVER, then, operates by obtaining, as user input, the definition of the solution type, the columns in the data base in which the hydraulic scenario is stored, the columns in the data base for which node/link data (e.g., nodal costs),

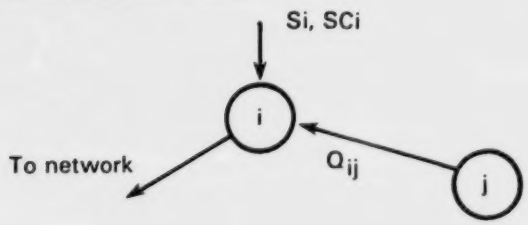
Theoretical Formulation



Mixing takes place at external supply node i

$$C_i = \frac{S_i S_{ci} + C_j Q_{ij}}{S_i + Q_{ij}}$$

Program Implementation



$C_j = SC_i$

No mixing

Equivalent Network Formulation

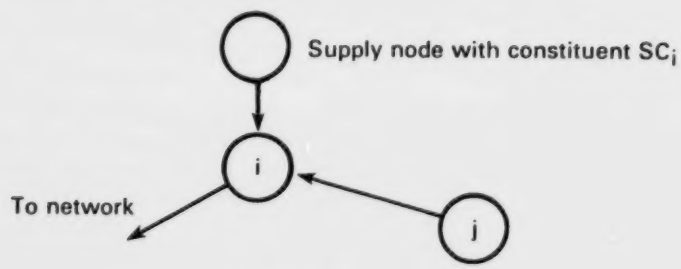


Figure 8: Boundary conditions at supply nodes.

travel times) are stored, and the column in the node file to which output is to be assigned, and the values of the constituent at external supply nodes.

CASE STUDY

In order to display some of the features of the WSSM, and to serve as a small, manageable system for testing of various WSSM elements, the village of New Vienna, Ohio, water supply system was selected for use as an example. While the system itself is relatively simple, it does provide sufficient complexity to display the nature of the WSSM. Other features leading to the selection of New Vienna were the availability of existing mappage and relatively detailed information associated with demands, costs, and system characteristics.[13]

THE NEW VIENNA SYSTEM

New Vienna is a village of approximately 1000 population (1980), located in Clinton County in Southwestern Ohio. A map of the village is shown is Figure 9. The water supply system serves approximately 900 residents, with some 340 residential meters. In addition, light industry, laundromats, and schools are served from the system. Average metered use in the village is approximately 1.7 million gallons per month.

Water is supplied to the system from two sources: a well field and treatment plant, operated by the Village, and purchased water from Highland County. The Village is required to purchase a set amount of water each month from Highland County, and operates so as to purchase that amount of water, then switches over to its local sources. In any month, typically two-thirds of the water will be purchased. Both sources do not operate simultaneously.

The distribution system consists of pipes 8" and under, with the majority at 4". The system dates back to 1903. A single elevated storage tank, with a

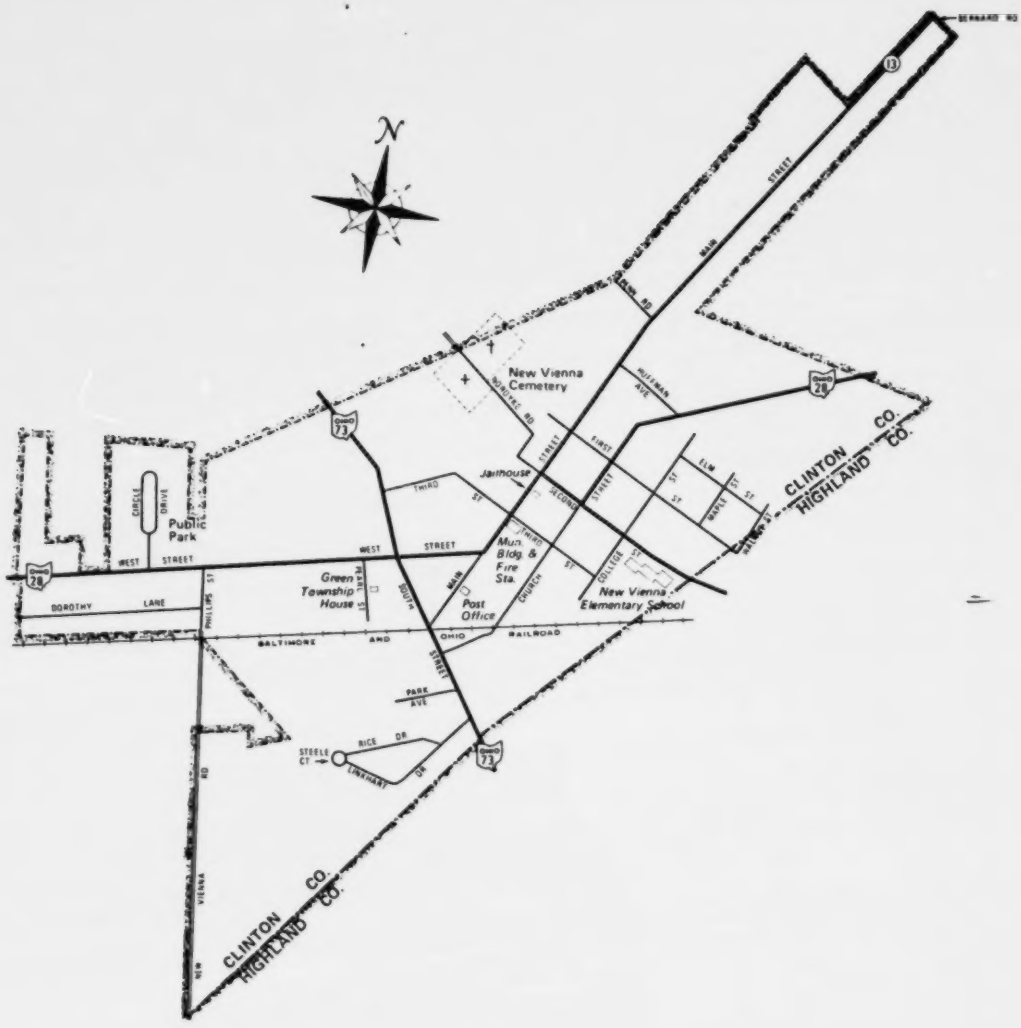


Figure 9: Map of New Vienna, Ohio

capacity of 50,000 gallons, serves the system to provide load leveling and minimal fire protection. Additional storage is required, and plans are under development to provide this capacity. The current system operates based on the level in the elevated storage tank - either the purchased water or the treatment plant, depending upon the mode the system is operating in, is switched on and off based on a pressure of 47 psig to start pumping, and 52 psig to stop pumping. The system is shown schematically in Figure 10.

The elevations in New Vienna range from approximately 1110 feet to 1180 feet. The average total head for the overall system is approximately 1240 feet. Low pressures in the range of 23 psig exist in the higher elevation portions of the village during normal operating situations, and under fire-fighting situations pressures may drop as low as 0 to 12 psig in certain areas.

Detailed base mappage, showing terrain, pipes, and location of existing buildings is available as a scale of 1" = 200'.

DATA BASE DEVELOPMENT

Development of the New Vienna Data Base consisted of the following steps:

a. delineation of the system in link-node form

b. determination of physical system characteristics (pipe size, diameter, etc.) and spatial coordinates.

c. development of demand data

d. development of cost data.

There is, of necessity, some interplay among these efforts, to insure that the link-node representation does portray the important changes in physical system character.

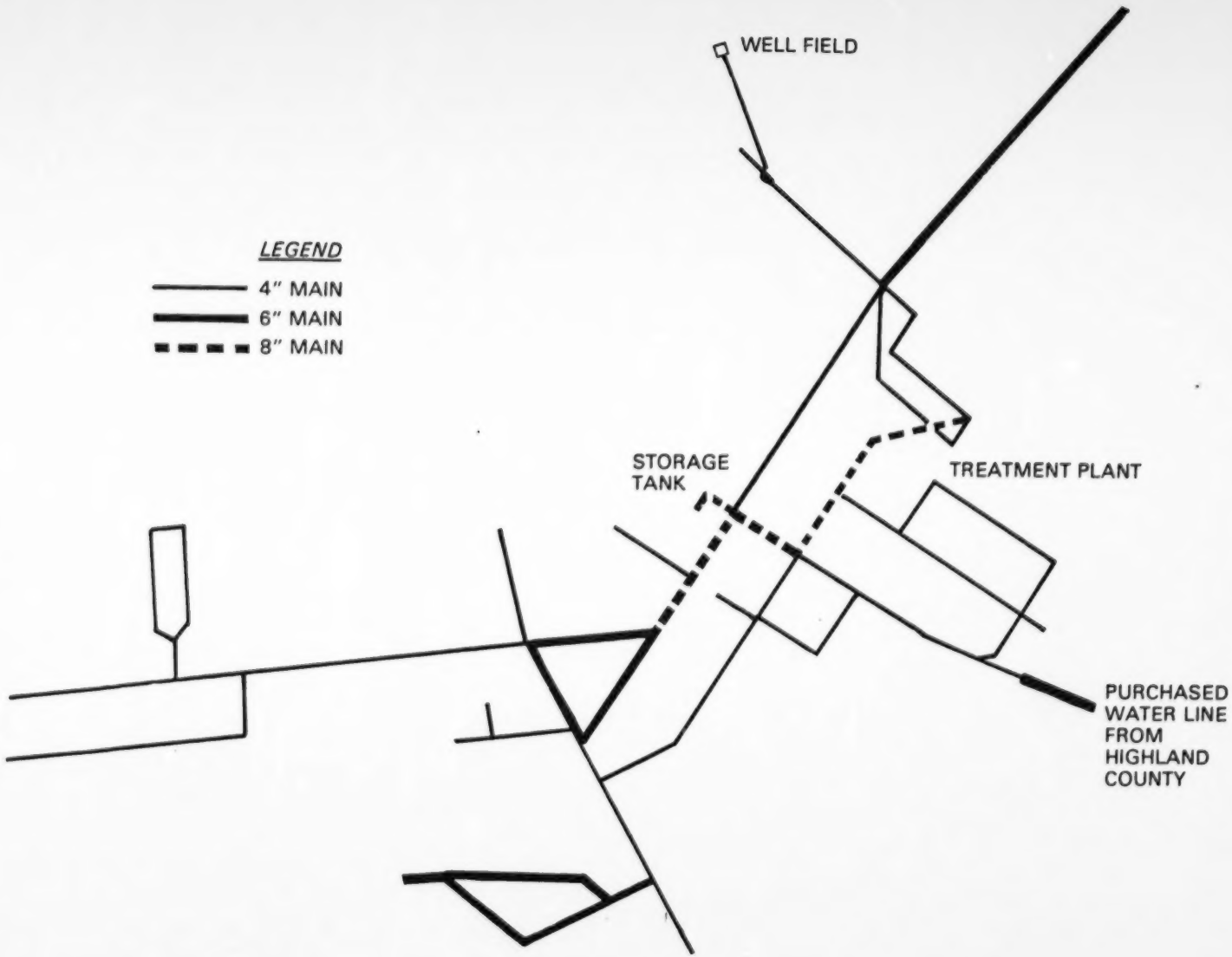


Figure 10: New Vienna System Schematic.

Delineation of System in Link-Node Form

A link-node representation of the New Vienna water system was laid out on a gridded overlay to the 1" = 200' base map. Nodes were located in continuous lengths of pipe, based on their serving as centers of aggregation of demand. Nodes were also located at pipe junctions, and changes in pipe diameter or type. The system was also laid out so that nodes were located at major changes of pipe direction, to provide an accurate geometric as well as topologic map of the system. All pipes were represented, except for service connections. Thus, the link-node representation is a fairly detailed, spatially reasonable one. In larger and more complex systems, not all pipes would be represented, and there would in general be a less faithful representation of the actual "map" of the system. Each link and node was numbered sequentially. The New Vienna Link-Node representation consists of approximately 50 links and 50 nodes. The Link-Node representation of the New Vienna System is shown in Figure 11.

Determination of Physical System and Spatial Characteristics

Pipe lengths, types, and diameters are available from the base map. This information was transferred to the link-node system, and associated with each individual link number. Topological data, in the form of the "upstream" and "downstream" node numbers for each link was also taken off and recorded. This information serves to set the convention for flow throughout the WSSM, as well as providing topologic connectivity. By convention, flow in the pipe from upstream to downstream node is positive, and flow into a node is positive.

The coordinate locations of each node are recorded in digital form. Elevations were obtained by placing the overlay on top of the base map, and reading the elevation at each node

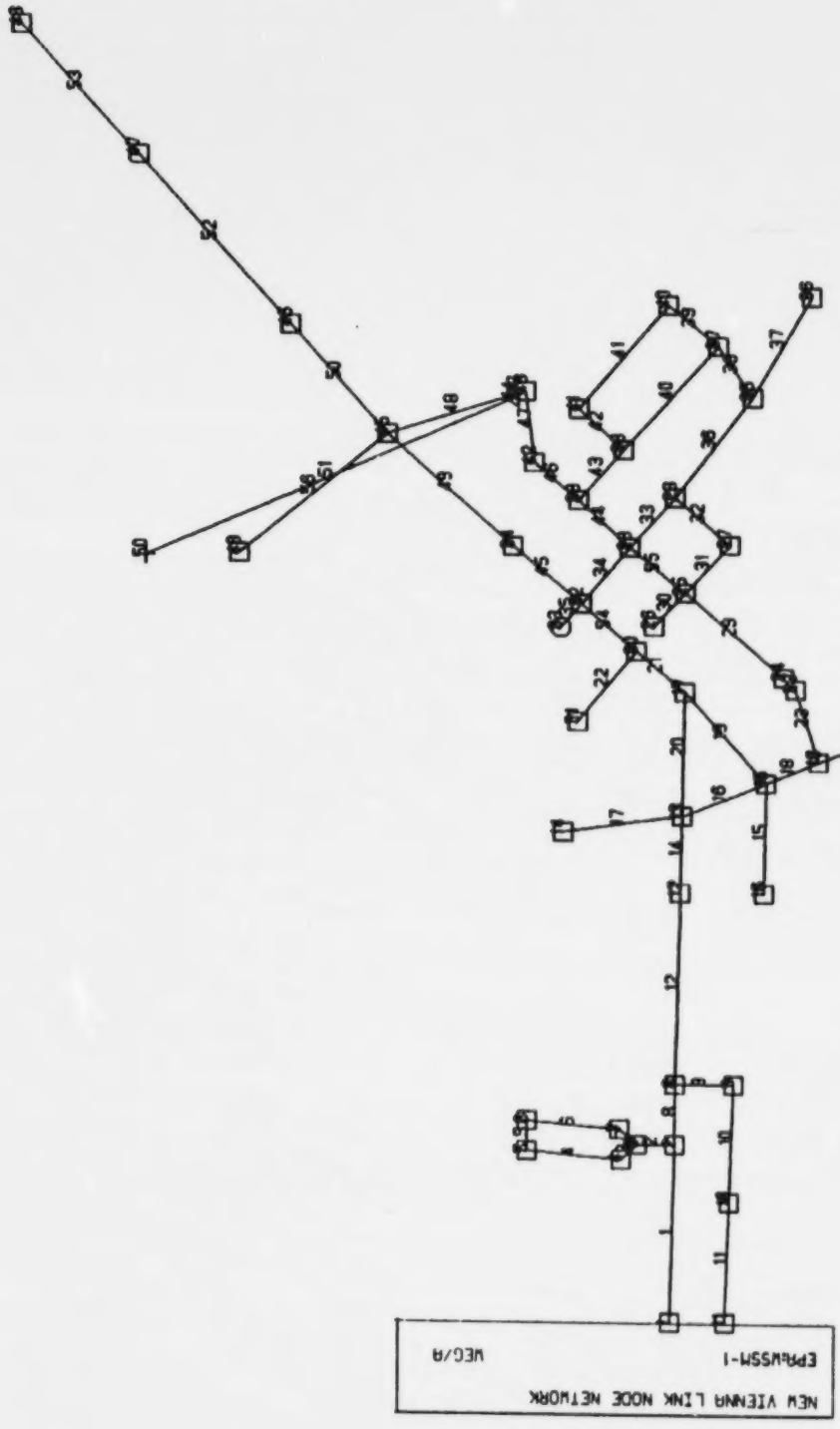


Figure 11: New Vienna Node-Link Representation.

from the contours on the base map. (Contours on the base map are at 3' intervals). Data for both the links and nodes were encoded, and prepared as input to the file establishment module of WSSM. The encoded data is shown in Figure 12.

DEVELOPMENT OF DEMAND DATA

While metered information is available for the majority of the Village, demand data was developed, for other than industrial users, by performing "house counts" within demand zones. Demand zones were drawn on the link-node overlay, to arbitrarily associate demands with nodes. Each node has a demand zone, and it is assumed that any demands falling within that area are aggregated to the node. A count of houses for each demand zone was obtained by placing the demand zone overlay on top of the base map showing house locations, and each house was assigned a demand equal to the average residential demand for New Vienna, estimated to be 3738 gallons per meter per month. Concentrated demands associated with industry and public uses were estimated from meter readings, and assigned to the appropriate demand zone. Total demand within each demand zone was then calculated, and entered into the data base as a characteristic of the node associated with the demand zone. Because of the steady-state analysis, demands are quite small, and are expressed in gallons per minute. In a small community such as New Vienna, the majority of residential demand will take place at relatively well-defined morning and evening periods, thus adjustments to the demand arrived at by assuming a continuous use are appropriately made, consistent with knowledge of the use pattern in the area. This adjustment was applied to New Vienna in the data presented here, assuming that average monthly demand is exerted over six hours each day.

	ABC	D	E	F	G
1	11137	80	1860	4	-0.086
2	11125	1140	1840	5	-0.516
3	11122	1140	2060	4	-0.086
4	11124	1050	2150	4	-0.172
5	11122	1100	2700	4	-0.344
6	11125	1280	2700	4	-0.516
7	11118	1230	2160	4	-0.086
8	11123	1500	1840	4	-0.602
9	11121	1500	1500	4	-0.516
10	11132	800	1520	5	-0.774

Sample ESTBNODE Input
A: Node Number, B: Node Type, C: Node Elevation (feet)
D: Node X - Coordinate, E: Node Y - Coordinate
F: Zone, G: Demand at Node

	AB	C	DE	F	G	H	I
1	1	2	155	2	130.	1040.	4.
2	1	2	357	2	130.	220.	4.
3	1	3	457	2	130.	120.	4.
4	1	4	557	2	130.	550.	4.
5	1	5	657	2	130.	180.	4.
6	1	6	757	2	130.	550.	4.
7	1	7	357	2	130.	120.	4.
8	1	8	2	2	130.	360.	4.
9	1	8	961	2	130.	330.	4.
10	1	9	1061	2	130.	700.	4.

Sample ESTBLINK Input
A: Link Number, B: Link Type, C: Upstream Node
D: Downstream Node, E: Year Installed (19xx), F: Material Code,
G: C Factor, H: Length (feet), I: Diameter (miles)

Figure 12: Sample input for ESTBNODE and ESTBLINK.

Development of Cost Data

The economic allocation procedure, at its current state of devlopment, requires a single annualized cost, representing the combination of amortized capital and O&M costs, for each node and link. The rules used in the case study for attributing costs to nodes and links were as follows:

links - capital costs as capital cost of link itself, actual construction cost where possible, estimated otherwise. Hydrant costs are assigned to links. Operation and maintenance cost assigned directly to links where identifiable, allocated based on ratio of link length to total system length otherwise.

nodes - actual or estimated costs of node structure (tank, treatment plant). No cost associated with junctions. Capital cost of all the demand zone service connections within a demand zone assigned to the node for the demand zone. Where possible, separately identifiable O&M costs are assigned to each node. Water purchase cost is assigned as an annual cost at the node where water is purchased. O&M cost associated with service connections is allocated to nodes based on the ratio of the nodal capital cost to the total capital cost of all service connections.

As can be seen, these rules rely upon information relating to the demand zones. These rules seem reasonable for the New Vienna example. Other situations may require a different set of cost allocation rules. The important feature is, of course, that of consistency in application of the rules, and careful documentation of decisions made in the cost allocation process.

For the case of New Vienna, actual construction cost was not available for most elements.[13] Capital costs in general were estimated as current

replacement costs, and then revised to actual year of installation through use of the three digit Engineering News Record Construction Cost Index. The existing well and water treatment system costs were estimated based on cost curves derived from "Estimating Water Treatment Costs".[14] Bid data for replacement of the elevated storage tank was used to estimate its replacement cost. Pipe costs were developed based on unit prices in a construction bid for the area. All estimated costs were first calculated on a 1981 basis before being revised to year of installation. The base year of the CCI is 1913, thus all system elements known to be installed prior to that date were treated as if they had been installed in 1913.

Annual O&M costs are as shown in the Table 4. Total 1981 O&M cost, including debt service and administrative costs, was projected to be $46,721. The distribution of O&M cost and Debt Service to various system elements is shown in Table 4. Costs were allocated as indicated above. Nodal and link cost summaries, showing the 1981 construction cost, year of construction, CCI factor, original construction cost (computed), and 1981 O&M cost, are shown in Tables 5 and 6.

EXAMPLE OF WSSM USAGE FOR NEW VIENNA

The preceding section contains a description of how data for a WSSM data base is developed. This section contains a description of how that information is used within WSSM, the flow of information between the various programs of WSSM, and examples of program input and output. The information presented relative to each program is only an overview - detailed descriptions of each program, its input and output, are contained in volume III of this report series. Thus, the information contained herein is not a "User's Guide", but is presented to show and describe the nature of WSSM information flow, and typical intermediate and final products.

TABLE 4. NEW VIENNA WATER SYSTEM OPERATION AND MAINTENANCE COSTS FISCAL YEAR 1979

Elected Official	$ 150.00
Trustee Pay Agent	300.00
Bonds	71.00
Transfers	3,431.72
Refunds	0
Maintenance of Equipment	1,159.76
Chemicals, Supplies and Meters	1,139.62
Capital Improvement (Water tower Painting)	1,850.00
Personnel Salary	9,249.96
PERS Village (Retirement)	1,032.02
Fuel and Light	2,513.47
Office Expense	805.59
Highland County Water Company Water Purchase	18,027.93
Bond Return (Principal and Interest)	5,505.00
TOTAL	$45,236.07

This original construction cost, current O&M cost, and year of construction were inserted into the data base for each link and node.

TABLE 5. NODE COST SUMMARY

NODE	1981 CONST. COST	1981 O&M COST	YEAR OF CONST.	CCI FACTOR	ORIGINAL CONST. COST	NOTES
1	900	12.60	1955	.182	163.80	
2	5,400	75.30	1955	.182	982.80	
3	900	12.60	1957	.1991	179.19	
4	1,800	25.10	1957	.1991	358.38	
5	3,600	50.20	1957	.1991	716.76	
6	5,400	75.30	1957	.1991	1,075.14	
7	900	17.60	1957	.1991	179.19	
8	6,300	87.70	1955	.1991	1,146.60	
9	4,500	62.60	1961	.182	1,062.45	
10	8,100	111.80	1961	.2361	1.912.41	
11	4,500	62.60	1961	.2361	1,067.45	
12	3,600	50.20	1955	.2361	655.20	
13	15,300	213.20	1913	.182	434.52	
14	7,100	100.50	1913	.0284	204.48	
15	11,700	163.00	1913/61	.0284	1,547.91	
16	3,700	37.40	1913	.1323	105.08	Includes 1-1/2" pipe & service
17	16,200	226.00	1913/61	.0284	2,143.26	
18	7,200	100.50	1913	.1323	204.48	
29	9,000	125.40	1913	.0284	255.10	
20	5,400	75.30	1969	.0284	1,861.38	
21	2,700	32.40	1969	.3447	930.69	
22	1,800	25.10	1969	.3447	670.46	
23	5,400	75.30	1913	.3447	155.36	
24	6,300	87.70	1913	.0284	178.92	
25	10,800	150.70	1913/67	.0284	1,735.56	
26	1,800	25.10	1967	.1607	527.40	
27	9,000	125.40	1913	.293	255.60	
28	12,600	175.80	1913	.0284	357.84	
29	10,800	150.70	1913	.0284	306.72	
30	7,200	100.50	1913	.0284	204.48	
31	9,000	175.40	1971	.4195	3,775.50	
32	11,700	163.00	1913	.0284	332.28	
33	147,600	855.00	1913	.0284	4,191.84	Water tower
34	15,300	213.20	1913	.0284	434.52	
35	10,800	150.70	1913	.0284	306.72	
36	3,600	18,078.20	1969	.3447	1,240.92	Water Purchase
37	9,000	125.40	1950	.1365	1,228.50	
38	6,300	87.70	1950	.1365	859.95	
39	9,000	125.40	1950	.1365	1,228.50	
40	8,100	112.80	1950	.1365	1,105.65	
41	3,600	50.20	1950	.1365	491.40	
42	3,600	50.20	1913	.0284	102.24	
43	2,700	37.40	1962	.2418	652.81	
44	256,627	17,449.00	1961	.2361	60,589.64	Treatment Plant
45	18,000	250.70	1962	.2418	4,352.40	
46	9,000	125.40	1961	.2361	2,124.40	
47	13,500	188.10	1961	.2361	3,187.35	
48	4,500	62.60	1961	.2361	1,062.45	
49	900	17.60	1962	.2418	217.62	
50	41,870	3,824.00	1961	2361	9,873.70	Wells

TABLE 6. LINK COST SUMMARY

LINK	COST CONST.	YR OF CONST.	CCI FACTOR	ORIGINAL CONST.COST	1981 O&M COST
1	3,380	1955	.182	706.16	33.78
2	440	1957	.1991	87.60	3.80
3	1,380	1957	.1991	274.76	11.99
4	2,000	1957	.1991	398.20	17.39
5	1,260	1957	.1991	250.87	11.00
6	2,000	1957	.1991	398.20	17.39
7	480	1957	.1991	95.57	4.20
8	1,620	1955	.182	294.84	13.99
9	900	1961	.2361	212.49	7.80
10	3,200	1961	.2361	755.52	27.79
11	2,340	1961	.2361	552.47	20.39
12	8,763.50	1955	.182	1,594.96	76.16
14	3,637	1955	.182	661.93	31.58
15	4,827	1913	.0284	137.09	41.98
16	4,293.50	1913	.0284	121.94	37.18
17	5,305	1913	.0284	150.66	45.98
18	2,203.50	1913	.0284	62.58	19.19
19	7,920	1961	.2361	1,869.91	68.77
20	6,703	1913	.0284	176.17	53.77
21	4,810	1913	.0284	136.60	41.78
22	2,240	1971	.4195	939.68	19.39
23	3,578	1913	.0284	101.62	30.99
24	4,470	1913	.0284	126.95	38.78
25	1,361	1969	.3447	469.14	11.79
26	4,005	1969	.3447	1,380.52	34.78
27	3,697.50	1969	.3447	1,274.53	32.18
28	2,625	1969	.3447	904.84	22.79
29	7,222	1913	.0284	205.11	62.77
30	960	1967	.293	281.28	8.40
31	2,620	1913	.0284	74.41	22.79
32	4,180	1913	.0284	118.71	36.38
33	2,620	1913	.0284	74.41	22.79
34	5,828	1913	.0284	165.52	50.58
35	3,473	1913	.0284	98.63	30.19
36	3,221.25	1913	.0284	91.48	27.99
37	3,714.30	1955	.182	681.50	32.58
38	960	1972	.4793	460.13	8.40
39	770	1972	.4793	345.10	6.20
40	2,540	1950	.1365	346.71	21.99
41	2,520	1950	.1365	343.98	21.99
42	40	1950	.1365	128.31	8.00
43	1,040	1950	.1365	141.96	9.00
44	5,492	1913	.0284	155.97	47.48
45	4,185.50	1913	.0284	118.87	36.38
46	4,820	1913	.0284	136.89	41.98
47	5,149	1913	.0284	153.10	44.78
48	6,552.50	1962	.2418	1,584.40	56.97
49	6,850	1913	.0284	194.54	59.57
50	9,992.50	1961	.0361	2,262.43	83.16

Once the basic description of the link-node network and its physical characteristics has been obtained, the data is encoded, as shown previously in Figure 12. This data is then used as input to the data base establishment programs, ESTBLINK and ESTBNODE. An example of the output of each of these programs is shown in Figure 13. Program ERCHECK is run to test for topologic errors. Sample output is shown in Figure 14. At this point, it is frequently desirable to be able to visually inspect the data base, and to be able to refer back directly to the base map. Accordingly, program NETPLOT is utilized to obtain a computer plot at desired scale, of the network. An example of a portion of a typical plot provided by NETPLOT is shown in Figure 15. Program REPORTER is also run to obtain a listing of the data base, showing what has actually been stored for each pipe and node. An example of typical output from REPORTER for the link and node files is shown in Figure 16.

The information generated in this first phase of data base establishment is then utilized in the edit/checking phase. The spatial location of nodes, the connection of nodes and pipes, and the characteristic data associated with each pipe and node, are checked, making use of the plot, file listings from REPORTER, and any output messages of the file establishment module programs. Corrections are made by use of the EDITOR Module programs FIXL and FIXN, for topologic and geometric data, and INSELK and INSEND for attribute data. Sample input and output of each of these programs is shown in Figure 17. The process at this point becomes an iterative one, in which modifications are made to the data base, and the error checking and display facilities of WSSM are utilized to uncover any discrepancies. At some point, the data base is declared to be correct, or "clean".

At this point, it is usually desired to run the hydraulic analysis program. This is accomplished by first storing, in the data base, information about the

```
 BEGIN FILE ESTABLISHMENT PROCESS FOR USSM  NODE FILE TO BE CREATED,LINK FILE TO BE ZEROED
  BEGUN ON 820323 AT 105551
  NODE FILE HAS    11 PHYSICAL RECORDS ROOM FOR    100 LOGICAL NODE RECORDS
 LINK FILE HAS    11 PHYSICAL  RECORDS ROOM FOR    100 LOGICAL LINK RECORDS
  BAD INPUT CARD        3    1     1122.     1140.     2060.    4    0       -0.        0.        0.
 PROCESSING COMPLETE FOR NODE FILE ESTABLISHMENT MAX NODE RECORD IS   50NUMBER OF CARDS PROCESSED IS   50
   NUMBER OF CARDS REJECTED IS     1
 +++++ BOUNDING RECTANGLE ++++++++
             N      5690.
   E        80.          7760. E
             N       200.
 +++++ BOUNDING RECTANGLE ++++++++
03-23-8210:55:51
  ECHO    1  11137.        80.      1860.    4    0   -0.    0.        0.        0.        0.
  ECHO    2  11125.      1140.      1840.    5    0   -1.    0.        0.        0.        0.
  ECHO    3  11122.      1140.      2060.    4    0   -0.    0.        0.        0.        0.
  ECHO    4  11124.      1050.      2150.    4    0   -0.    0.        0.        0.        0.
  ECHO    5  11122.      1100.      2700.    4    0   -0.    0.        0.        0.        0.
  ECHO    6  11125.      1280.      2700.    4    0   -1.    0.        0.        0.        0.


  BEGIN LINK FILE ESTABLISHMENT     ON  820323  AT  105818
 NODE FILE ACCESS PROBLEMS
  LINK     6 WITH NODE   67 HAS ISTAT    2 IBLOCK    1020
 PROCESSING COMPLETE MAX. LINK NUMBER IS   57
  CARDS CORRECTLY USED    56 NO. OF REJECTED IS     1
03-23-8210:58:18
  ECHO        1      1      0      0      2      1      4.0000      1040.  550000   130.      0.      0.
  ECHO        2      1      0      0      2      3      4.0000       220.  570000   130.      0.      0.
  ECHO        3      1      0      0      2      3      4.0000       120.  570000   130.      0.      0.
  ECHO        4      1      0      0      4      5      4.0000       550.  570000   130.      0.      0.
  ECHO        5      1      0      0      5      6      4.0000       180.  570000   130.      0.      0.
  ECHO        6      1      0      0      6     67      4.0000       550.  570000   130.      0.      0.
  ECHO        7      1      0      0      7      3      4.0000       120.  570000   130.      0.      0.
```

Figure 13: Sample ESTBNODE and ESTBLINK output.

```
 TOPOLOGIC & GEOGRAPHIC ERROR SEARCH
  LARGEST USED NODE ID IS   50          LARGEST USED PIPE ID IS   57
  ERROR MESSAGE GENERATION ON 820323 AT 105958
     2    3 PIPES ARE PARALLEL BETWEEN NODES     2    3
     2    3 PIPES ARE PARALLEL BETWEEN NODES     3    2
 IN NODE REC    6 PIPE    6 LISTED IN CONNECTIVITY LIST DOES NOT EXIST I/O ISTAT IS 2
 ERR MESSAGE COMPLETED
03-23-8210:59:58
 NETWORK ENDS
 NODE     1      TYPE ONE      IN ZONE       4.
 NODE     4      TYPE ONE      IN ZONE       4.
 NODE     7      TYPE ONE      IN ZONE       4.
 NODE    11      TYPE ONE      IN ZONE       5.
 NODE    14      TYPE ONE      IN ZONE       4.
 NODE    31      TYPE ONE      IN ZONE       2.
 NODE    23      TYPE ONE      IN ZONE       6.
 NODE    24      TYPE ONE      IN ZONE       6.
 NODE    26      TYPE ONE      IN ZONE       7.
 NODE    33      TYPE TWO      IN ZONE       2.
 NODE    36      TYPE ONE      IN ZONE       8.
 NODE    50      TYPE  FOUR    IN ZONE       1.
 NODE    48      TYPE ONE      IN ZONE       1.
 NODE    49      TYPE ONE      IN ZONE       1.
```

Figure 14: Sample ERCHECK output.

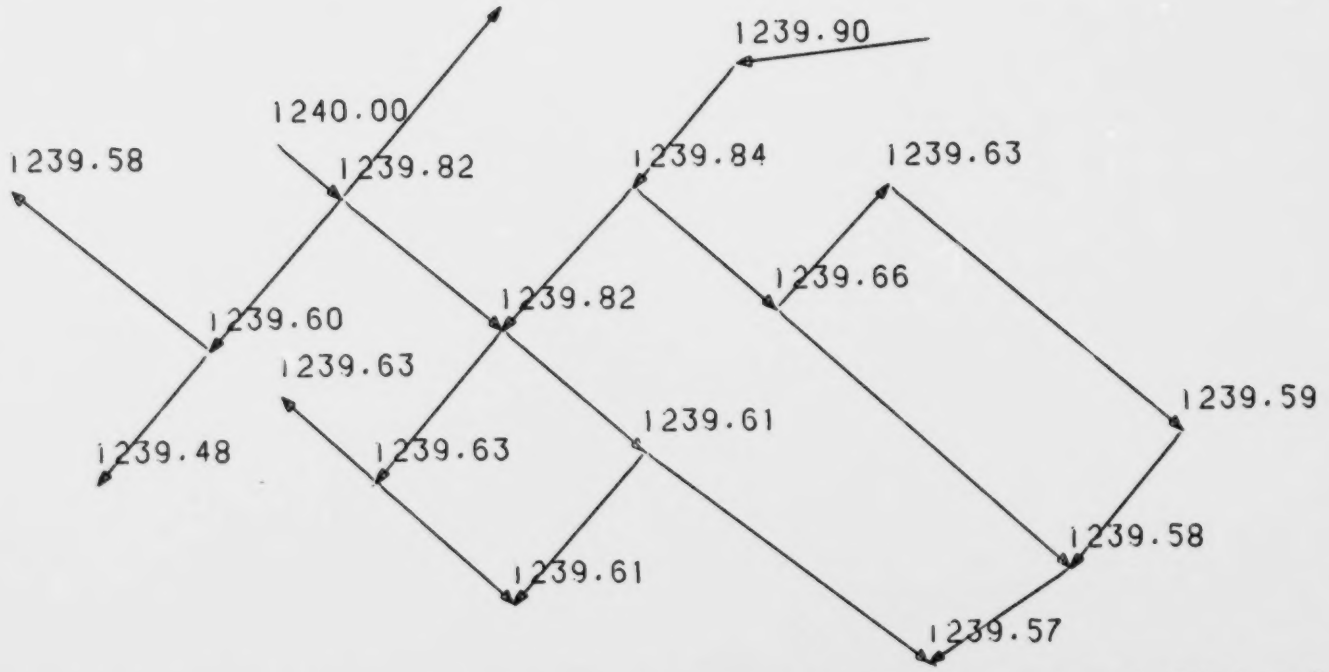


Figure 15: NETPLOT plot showing total head at nodes and flow direction as stored in data base for a hydraulic scenario.

PAGE 1
DATE 820323
TIME 103500
NODE FILE
RECORDS

U S S M - 1
NEW VIENNA WATER
NODE FILE REPORT 1-10

		DESCRIPTIONS						
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
REC NO	1	1.00	1.00	4.00	0.0	80.00	1860.00	1137.00
REC NO	2	2.00	1.00	5.00	0.0	1140.00	1840.00	1125.00
REC NO	3	3.00	1.00	4.00	0.0	1140.00	2060.00	1122.00
REC NO	4	4.00	1.00	4.00	0.0	1050.00	2150.00	1124.00
REC NO	5	5.00	1.00	4.00	0.0	1100.00	2700.00	1122.00
REC NO	6	6.00	1.00	4.00	0.0	1280.00	2700.00	1125.00
REC NO	7	7.00	1.00	4.00	0.0	1230.00	2160.00	1118.00
REC NO	8	8.00	1.00	4.00	0.0	1500.00	1840.00	1123.00
REC NO	9	9.00	1.00	4.00	0.0	1500.00	1500.00	1121.00
REC NO	10	10.00	1.00	5.00	0.0	800.00	1520.00	1132.00

PAGE 1
DATE 820323
TIME 103918
LINK FILE
RECORDS

U S S M - 1
NEW VIENNA WATER
LINK FILE REPORT 1-10

		DESCRIPTIONS						
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
REC NO	1	1.00	1.00	0.0	0.0	2.00	1.00	1140.00
REC NO	2	2.00	1.00	0.0	0.0	2.00	3.00	1140.00
REC NO	3	3.00	1.00	0.0	0.0	3.00	4.00	1140.00
REC NO	4	4.00	1.00	0.0	0.0	4.00	5.00	1050.00
REC NO	5	5.00	1.00	0.0	0.0	5.00	6.00	1100.00
REC NO	6	6.00	1.00	0.0	0.0	6.00	7.00	1280.00
REC NO	7	7.00	1.00	0.0	0.0	7.00	3.00	1230.00
REC NO	8	8.00	1.00	0.0	0.0	8.00	2.00	1500.00
REC NO	9	9.00	1.00	0.0	0.0	8.00	9.00	1500.00
REC NO	10	10.00	1.00	0.0	0.0	9.00	10.00	1500.00

Figure 16: Sample REPORTER output for Node and Link Files.

```
$RUN W.INSELK.O 6=-OUTPUT 10=-TIME 11=NEWV3.DA.NODE 12=NEWV3.DA.PIPE
  13    21 130.   26 375.70 27 5000.  28 43.40  29 1981.  31 332.30
  13    36 1.
9999
$ENDFILE


BEGIN INSERTION TO NODE FILE ON   820203 AT   163357  PROGRAM UPDATE CODE IS 3020
  33 NODE RECORD
32COLUMN VALUE    1240. REPLACES        0. 33COLUMN VALUE    1245. REPLACES        0.

  44 NODE RECORD
32COLUMN VALUE    1240. REPLACES        0. 33COLUMN VALUE    124' . REPLACES        0.

FILES CLOSED HEADER UPDATED ON   820203 AT  163357 CODE= 3020
```

a) Program INSEND input and output

```
$RUN W.INSEND.O 6=-OUTPUT 10=-TIME 11=NEWV2.DA.NODE 12=NEWV2.DA.PIPE
  33    32  1240. 33  1245.
  44    32  1240. 33  1245.
9999
$ENDFILE


:  BEGIN INSERTION TO PIPE FILE ON   820303 AT   140432  PROGRAM UPDATE CODE IS 3040
:    13 PIPE RECORD
:  21COLUMN VALUE        130. REPLACES          0. 26COLUMN VALUE        376. REPLACES          0.
:  27COLUMN VALUE       5000. REPLACES          0. 28COLUMN VALUE         43. REPLACES          0.
:  29COLUMN VALUE       1981. REPLACES          0. 31COLUMN VALUE        332. REPLACES          0.
:    13 PIPE RECORD
:  36COLUMN VALUE          1. REPLACES          0.
: FILES CLOSED HEADER UPDATED ON   820303 AT  140432 CODE= 3040
```

b) Program INSELK input and output

Figure 17: Sample input at output for file editing programs.

```
$RUN W.FIXL.O 6=-OUTPUT 10=-TIME 11=NEWV3.DA.NODE 12=NEWV3.DA.PIPE
  -13
    13   21    8           4.      1600.
99999
$ENDFILE
 BEGIN TOPOLOGICAL EDITING VIA PIPE FILE ON   820303 AT   121911
  INPUT CARD  -13    0    0     CORRECTIONS FOR DIAMETER   0. AND LENGTH         0.
    13 PIPE CONNECTING NODE    21 TO NODE     8 IS  TO BE DELETED !!!!!
      21 :PIPE LIST OLD:    26   27   13    0    0    0    0    0    0    0 NEW:    26   27    0
       8 :PIPE LIST OLD:     8    9   13    0    0    0    0    0    0    0 NEW:     8    9    0
 PIPE RECORD    13 IS DELETED FROM FILE
  INPUT CARD   13   21    8     CORRECTIONS FOR DIAMETER   4. AND LENGTH      1600.
    13 PIPE  *****  NEW RECORD ***** CONNECTS NODE    21 TO NODE     8
      21 :PIPE LIST OLD:    26   27    0    0    0    0    0    0    0    0 NEW:    26   27   13
       8 :PIPE LIST OLD:     8    9    0    0    0    0    0    0    0    0 NEW:     8    9   13
 END EDIT OF PIPE    13 (X,Y,Z)N1:      2300.      570. 1118. (X,Y,Z)N2:      1500.     1840. 1123.
  INPUT CARD99999    0    0     CORRECTIONS FOR DIAMETER   0. AND LENGTH         0.
 END TOPOLOGICAL EDITING
$RUN W.FIXN.O+W.IOMODULE.O+W.BRWRIT.O+W.DATIME.O 6=-OUTPUT 11=NEWV3.DA.NODE 12=NEWV3.DA.PIPE 10=-TIME
  -46
   12                        1112.
99999
$ENDFILE
 BEGIN COORDINATE EDITING OF NODE FILE ON  820401 AT  113429
 START EDIT FROM INPUT CARD  -46        0.        0.        0.
NODE:    46 ZEROED IN NODE FILE
LINK:    50 DELETED FROM LINK FILE
LINK:    52 DELETED FROM LINK FILE
 START EDIT FROM INPUT CARD   12        0.        0.     1112.
 NODE   12 OLD COORD:      2640.     1820.     1080. CORRECTIONS:        0.        0.     1112.
    LINKS CONNECTED TO NODE   12 ARE      14.      0.      0.      0.      0.      0.      0.      0.
    UPDATE PIPE    14 FROM NODE    12 OLD COORD:     2640.     1820.     1080. NEW  2640.     1820.
 END EDIT OF NODE    12
 START EDIT FROM INPUT CARD99999        0.        0.        0.
  NODE FILE EDITING COMPLETED, FILES CLOSED
```

Figure 17 (continued): FIXL and FIXW example input and output.

"scenario" that is to be run. A scenario is a particular set of links and nodes in the data base, that is to be extracted for submission to the hydraulic network analyzer. A scenario is described by values stored in columns in the node and link file. Each input scenario requires two columns in the node file and one column in the link file. The first nodal column specifies how the particular node is to be treated in the simulation (as a fixed head or a fixed flow node), and the second column defines the respective flow or head at the node, to be used in the simulation. In the link file, the scenario description column contains a numeric code describing the type of hydraulic element that the particular link is to be represented by in the simulation run (or whether the link is to be included in the simulation at all). Thus, the scenario is both a description of what hydraulic elements of the data base (nodes and links) are to be included in a particular network analysis, and a description of the manner in which these elements are to be represented to the simulation. This flexibility is important, because it is frequently necessary to represent something that is physically one kind of element, e.g. a tank, as another type of element, say a fixed demand, in order to get an appropriate representation, particularly when attempting to portray a dynamic system in a steady-state fashion.

Scenarios are defined and stored in the working space portion of the data base. It is important to maintain a record of what attribute data is stored in the fields of a particular set of link and node files, and to insure that consistent columns are specified as input to a given program - thus, if more than one scenario is developed, then each time a scenario is referenced it must have corresponding columns specified in the link and node files. Severe problems can result from specifying the nodal columns associated with scenario #1 together with the link file column associated with scenario #2.

Programs LCOPYATT and NCOPYATT are provided as utilities to allow for greater ease in specifying scenarios. These programs simply copy one column of a data file to another column of the same file. Thus, if scenario #2 is a slightly modified version of scenario #1, the NCOPYATT and LCOPYATT series of programs are used to duplicate all the columns of scenario #1 in other data base columns; then, only the individual links or nodes that require modification are changed with the INSEND and INSELK utilities. The scenario specification in a data base is easily checked through use of the REPORTER output lists.

Once the scenario has been inserted into the data base, the WATINT program can be run. This program generates a card-image data file in precisely the format necessary to run the WATSIM model. Input to the program is simply three numbers, specifying the scenario columns in the node and link file. It is also possible to specify a factor that determines approximation of head at each node that WATSIM uses as an initial trial solution, but default values are provided if this number is not specified. A sample input and output of this program is shown in Figure 18.

The output from WATINT is a card-image data set. The user must then prefix certain WATSIM header cards to this data set. These header cards are title cards, run parameters, and the like, and, with the exception of the title cards, will generally be standard information. The combined data file of header and WATINT output is then ready for input to WATSIM, the hydraulic network analysis model.

WATSIM is the hydraulic network analysis program currently utilized with WSSM. It takes as input a set of run parameters, and information describing each node, (demand type and elevation) and each link, (type, connectivity to nodes, length, C factor, and diameter). WATSIM is itself a large and complex

```
$RUN U.WATINT.U 6=-OUTPUT5 10=-TIME3 11=NEWV2.DA.NODE 12=NEWV2.DA.PIPE 9=U.NVS2
   31   33
   36
$ENDFILE
```

Sample input to WATINT

```
ENTER NODE COLUMNS - SCENARIO/FLOWS-HEADS/ELEV.INC  (DEFAULT=100FT.) IN 215,F10.0
WATSIM LINE AND NODE DECK
ON 820203 AT 164702 FOR      NEW VIENNA WATER          FILE
USING NODE COLUMNS    31   33 ELEVATION INC.=    100.0000
ENTER COLUMN FROM LINK FILE FOR SCENARIO (15)
AND LINK COLUMN    36
END DECK PROCESSING
```

Sample printed output of WATINT

```
                NO        1     1   0.0     1137.    1237.      0.      0.
                NO        2     1   0.0     1125.    1225.      0.      0.
                NO        3     1   0.0     1122.    1222.      0.      0.
                NO        4     1   0.0     1124.    1224.      0.      0.
                NO        5     1   0.0     1122.    1222.      0.      0.
                NO        6     1   0.0     1125.    1225.      0.      0.
                NO        7     1   0.0     1118.    1218.      0.      0.
                NO        8     1   0.0     1123.    1223.      0.      0.
                NO        9     1   0.0     1121.    1221.      0.      0.
                NO       10     1   0.0     1132.    1232.      0.      0.
```

Sample node deck output of WATINT

```
L       2     1     1     1      1040.    4.00   130.00    0.0          1
L       2     1     3     1       220.    4.00   130.00    0.0          2
L       3     1     4     1       120.    4.00   130.00    0.0          3
L       4     1     5     1       550.    4.00   130.00    0.0          4
L       5     1     6     1       180.    4.00   130.00    0.0          5
L       6     1     7     1       550.    4.00   130.00    0.0          6
L       7     1     3     1       120.    4.00   130.00    0.0          7
L       8     1     2     1       360.    4.00   130.00    0.0          8
L       8     1     9     1       330.    4.00   130.00    0.0          9
L       9     1    10     1       700.    4.00   130.00    0.0         10
```

Sample link deck output of WATINT

Figure 18: Sample WATINT input and output.

program, with complete documentation and example runs.[11] Minor modifications have been made to the WATSIM program so that it provides, in addition to its normal printed output describing pressures, flow, velocities, and head loss, (Figure 19), an output card-image data file that is in itself a summary for each node, of the pressure, head, and flow, and for each link, of the flow, and velocity, resulting from the particular set of input conditions. An example of this card-image data file is shown in Figure 20.

This WATSIM output file is then used as data input to program WATWSSM, the program that reinserts any portion of this data back into the data base, in user specified columns. Thus, the user may elect to insert only the nodal pressures back into a specified column of the node file, or may insert any of the data related to the node or link. This re-inserted data obviously is the "output scenario" corresponding to the specific "input scenario" used to generate the WATSIM input deck (through program WATINT). As noted previously, it is the responsibility of the user to externally keep all of this column usage straight. In particular, the SOLVER program requires as input corresponding information from both the input and output columns of a given scenario, and incorrect specification will result in inconsistent answers. A sample of the output of program WATWSSM is shown in Figure 21.

At this point, the data base contains hydraulic information (nodal pressures and heads, pipe flows and velocities) that allow the routines of SOLVER to be used. Additionally, any continuous nodal data (e.g. elevation, pressure, cost, concentration, travel time, etc.) can also be displayed as a contour plot. The current implementation of WSSM, installed on the University of Michigan Computer, operating under MTS, the Michigan Terminal System, utilizes a contouring program that is available as a utility on that system, and is thus

Reproduced from best available copy.

```
                    WATER NETWORK SIMULATION
                    ------------------------

                          RUN PARAMETERS

NEW VIENNA WATER SYSTEM
SCENARIO 1, RUN 1 2/3/82
          I/O FLOW UNITS ARE  GAL/MIN . UNIT CONVERSION FACTOR IS   0.0022272
          HAZEN-WILLIAMS EQUATION USED IN SOLUTION
          A STATIC SOLUTION IS BEING PERFORMED
          MINIMUM PRESSURE IN THE SYSTEM IS   40.  PSI
          MAXIMUM PRESSURE IN THE SYSTEM IS  140.  PSI
          MAXIMUM VELOCITY IN THE SYSTEM IS   10.  FEET/SEC
          UCI = 0.200
          ALPHABETICAL SORTING IS BY NODE NUMBER ONLY
          MAXIMUM NUMBER OF ITERATIONS ON NEWTON METHOD IS   20
          MAXIMUM MISMATCH TOLERANCE IS     0.000  CUFT/SEC
          HEAD TOLERANCE ON THE RESERVOIR HEAD VOLUME CALCULATION IS     0.100  FEET
          PRESWITCHING CORRECTOR DISCREPANCY TOLERANCE IS     0.200  FEET
          POSTSWITCHING CORRECTOR DISCREPANCY TOLERANCE IS     0.100  FEET
          SWITCHING SIMULTANEITY TOLERANCE IS     0.150  HOURS

                                                                          LO---LIMITS---HI
TYPE  NODE  ZONE  DESCRIPTION   FLOW       HEAD-FT  PSI AT ELEV  ELEV-FT              HWC     RES
                  (PAR)          GAL/MIN    (DROP)   (DEV-HEAD-FT) (LENGTH) DIAM-IN

NO    1     1                   -0.52     1236.203     42.945     1137.00
 L    2     1                   -0.52       -0.000                1040.0    4.00    130.0

NO    2     1                   -3.10     1236.203     48.140     1125.00
 L    1     1                    0.52        0.000                1040.0    4.00    130.0
 L    3     1                    7.23        0.013                220.0     4.00    130.0
 L    8     1                  -10.85       -0.045                360.0     4.00    130.0
```

Figure 19: WATSIM Sample Output.

Node	Pressure	Flow	Head
1	42.945	-0.520	1236.203
2	48.140	-3.100	1236.203
3	49.433	-0.520	1236.190
4	48.566	-1.030	1236.188
5	49.430	-2.061	1236.184
6	48.131	-3.099	1236.184
7	51.164	-0.520	1236.189
8	49.025	-3.610	1236.248
9	49.873	-3.100	1236.207
10	45.091	-4.640	1236.160
11	43.356	-3.100	1236.152
12	54.500	-3.610	1237.895
13	52.274	-8.760	1238.753
14	55.722	-4.130	1238.717
15	51.988	-17.830	1239.092
16	53.717	-1.550	1239.087
17	53.455	-9.292	1239.481
18	51.876	-4.130	1238.835
19	49.227	-5.160	1238.714
20	50.092	-3.100	1238.713

a) Node Data

Link	Flow	Velocity
1	0.520	0.020
2	7.230	0.283
8	10.850	0.424
3	3.548	0.139
7	-3.162	-0.124
4	2.518	0.098
5	0.457	0.018
6	-2.642	-0.103
9	10.840	0.424
12	25.300	0.990
10	7.740	0.303
11	3.100	0.121
14	28.910	1.131
17	4.130	0.162
16	-16.232	-0.635
20	25.568	1.000
15	1.550	0.061
19	53.682	0.933
18	18.070	0.707
21	88.541	0.866

b) Link Data

Figure 20· WATSIM card image output.

```
$RUN U.WATWSSM.0 6=-OUTPUT 10=-TIME 11=NEWV2.DA.NODE 12=NEWV2.DA.PIPE 14=-DEK1001
 34 35 36 38 39
$ENDFILE
```

a) Input runner for WATWSSM

```
 DATA BASE INSERTION PROCESSING FOR HYDRAULIC MODEL ON   820203 AT   172714
 NODE PRESSURE INSERTION COLUMN:    34
  NODE FLOW INSERTION COLUMN:    35
  NODAL HEAD INSERTION COLUMN   36
  LINK Q INSERTION COLUMN:    38
  LINK VELOCITY INSERTION COLUMN   39

    55 FLOWS INSERTED INTO FILE
 END INSERTION PROCESSING FOR HYDRAULICS
```

b) Output of WATWSSM

Figure 21: WATINT sample input and output.

Reproduced from best available copy.

not a part of WSSM. Such utility programs are widely available, however, and the necesssary interface to WSSM is not difficult.

The SOLVER routine can be operated in several different modes. In the concentration and travel-time modes, no additional data other than basic physical data and system hydraulics need be resident in the data base. In the cost mode, it is necessary that node and link annualized costs be stored in the data base. Capital, O&M costs, and year of construction, are presented for the New Vienna example and are used to develop annualized costs for each data base element. These costs are then used as input to SOLVER in the cost mode. An example of the input and output of SOLVER in this mode is presented in Figure 22; use of SOLVER in the other modes is similar. As noted previously, data output from SOLVER can be re-inserted directly into the data base, under user control, and used for later calculation, comparison, and display. A contour plot of the nodal data relating to unit cost of delivered water at a node, for the New Vienna example, developed through the contouring program of MTS, is shown in Figure 23.

The foregoing description of the WSSM usage environment may seem somewhat complex, but in practice it is not that difficult. WSSM has purposely been designed to be highly modular, and easily modified for a particular purpose. Thus, it is not a single program with a single input and output, and the user must be knowledgeable in more than just the requirements of such a single program. While it would be possible to "package" the elements of WSSM in a single module, the increase in complexity and the inherent loss of flexibility of such an approach dictate that WSSM remain highly modular, unless a particular user has a stable use environment and requires the additional ease of interaction that can be obtained from tighter "packaging". At present, as a research tool, it is preferable that the system remain open to change.

```
$RUN W.SOLVER.U 10=-TIME 6=-OUTPUT 3=W.SOLVS1.DAT 11=NEWV2.DA.NODE 12=NEWV2.DA.PIPE
31
  31  35  36  38      ANNUAL $/YR PER GPM COST $1
  41  26  60$/YR PER GPM
$ENDFILE
```

a) Sample Input

Reproduced from best available copy.

```
 TYPE  3 SOLUTION METHOD ON 820219 AT  94322 FOR      NEW VIENNA WATER
NODE   CONTROL   COLS:     31    35 LINK   CONTROL   COLS:     36    38 FOR    ANNUAL $/YR PER GPM COST $1
NODE INPUT COL=  41 LINE INPUT COL:  26 STORAGE COLUMN 60 VARIABLE DESCR: $/YR PER GPM
NUMBER OF PIPES MODELED =    55
 NUMBER OF NODES TO BE ORDERED    49

                                    NEW VIENNA WATER
DATE: 820219                    ANNUAL $/YR PER GPM COST $1
TIME:  94322       NODE SPECIFICATIONS     RESULTS OF ANALYSIS                PAGE  1
                                          NODE  $/YR PER GPM
                                           NO
                                            1          294.78
                                            2          108.09
                                            3          112.51
                                            4          133.36
                                            5          185.80
                                            6          198.05
                                            7          122.89
                                            8           93.90
                                            9          106.35
                                           10          144.60
                                           11          201.73
                                           12           80.21
                                           13           74.72
                                           14          110.19
```

b) Portion of Sample Output

Figure 22: SOLVER Input and Output.

Figure 23: Cost contours (cents/1000 gals.) for New Vienna (Scenario 1).

It will further be noted that WSSM does not in and of itself provide answers. It is, rather, a tool for managing and displaying water supply network data, coupled with the powerful analysis capabilities of WATSIM and SOLVER. The WSSM technology can aid the researcher, engineer, economist, or planner in a variety of ways, but in no sense can one "wind it up and let it give you the answers". The following section provides additional information relative to the conceptual basis, appropriate use environment, and potential arenas of application, of the WSSM technology.

FUTURE APPLICATIONS AND RESEARCH

The Water Supply Simulation Model is based on a number of useful concepts that provide a potentially powerful analysis technique. The fundamental structure is based on the use of data base management techniques interacting with special purpose analyical models. The unique concept employed in the WSSM is that of spatial analysis for engineering systems, using a network configuration.

DATA BASE MANAGEMENT AND MODELING

A relatively new technique developed to support engineering planning and design is that of the joint interactive use of computer simulation models and computer data bases. Data base in this context is best defined by a list of attributes as shown in Table 7. Traditionally data is collected to fit a particular mathematical model. The needs of the model selected for a particular analysis have traditionally defined the extent and character of the data collection and organization, and the organizing principle of the model becomes the organizing principle of the analysis. This "model/data" approach has become dominant in recent years. Conversely in a data base approach to analysis, information is organized in a manner suitable to the phenomenon at hand and not simply to "feed" a particular math model. In fact, in a proper formulation,

TABLE 7. PRIMARY OBJECTIVES OF DATA BASE ORGANIZATION

- The data can have multiple uses
- Intellectual investment is protected (programs need not be re-done when the data base is changed)
- Low Cost
- Less Data Proliferation - new application needs may be met with existing data
- Performance
- Clarity - users can easily know and understand what data is available to them
- Ease of Use - complexity is hidden from the users by the data base management system
- Flexible Usage
- Unanticipated requests for data can be handled quickly
- Change is easy
- Accuracy and Consistency - accuracy controls will be used
- Privacy - unauthorized access to the data will be prevented
- Protection from Loss or Damage
- Availability

"A data base may be defined as a collection of interrelated data stored together without harmful or unnecessary redundancy to serve one or more applications in an optimal fashion; the data are stored so that they are independent of programs which use the data; a common and controlled approach is used in adding new data and in modifying and retrieving existing data within the data base."

Ref: James Martin, Computer Data Base Organization, Prentice-Hall, 1975.

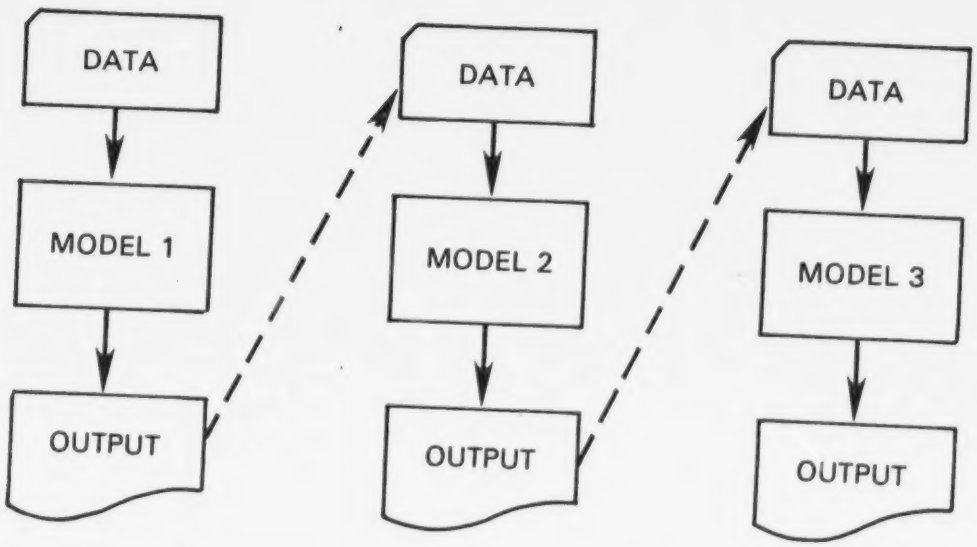
the data base can "feed" data to a variety of different models, increasing the flexibility/utility of the overall process. The distinction between the model-centered approach and the data-centered approach to data organization is shown schematically in Figure 24.

The overall concept of using mathematical models in conjunction with a data base has additional powerful advantages. Of primary significance is the opportunity to utilize a hierarchy of models - a set of mathematical models of differing degrees of complexity, specificity, data requirements, and costs, all operating upon the same data base. It is also possible to have a model re-insert the results of its analysis back into the data base, for later processing and analysis by yet another model.

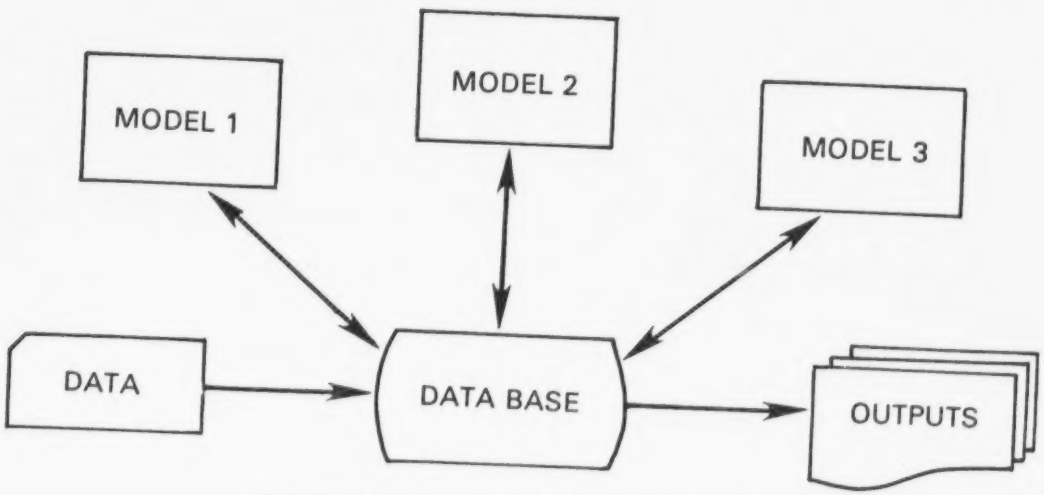
In summary, data management through use of a data base can be viewed primarily as an organizing principle for information; when models are applied to the information in the data base, a variety of analysis procedures and possibilities exist which are not so easily performed in the more common "model/data" approach to engineering analysis. By focusing on data base management as an organizer of information, a number of insights into both the problem at hand, and the analysis tools and techniques available, are possible. The concept of data centered modeling opens many new areas of research in environmental engineering.

SPATIAL ANALYSIS CONCEPTS

The concept of data centered modeling lends itself well to the idea of performing spatial analysis on engineering systems such as water distribution or other service delivery systems. The WSSM, while implemented as a set of computer programs, is in reality a somewhat different approach to problem-solving and analysis from that usually employed in "computer modeling". The approach employed in the WSSM is general in nature, and is not resticted to



MODEL-CENTERED ORGANIZATION



DATA-CENTERED ORGANIZATION

Figure 24: Model-Centered vs. Data-Centered Organization

water supply problems - in fact, it should find wide applicablity in analysis of a variety of kinds of service delivery systems that can be characterized as a distribution network overlaid on some spatial distribution of supply and demand. Transportation, power, and wastewater collection are additional arenas in which such an organizing concept applies.

Each element of spatial data has, at minimum, three characteristics:

- type - what it is (a tree, a dam, a river)
- measure or value - some numeric value defining how big, how much, etc.
- location - typically, some two- or three-dimensional coordinate system measure defining where the element is.

In some cases, a measure may be unimportant - it may be sufficient to know that a tree exists, with no concern for how tall it is.

To the above-noted three elements of spatial data, a fourth may be added - that of "neighborhood". The addition of this fourth characteristic, as either an explicit or implicit property of spatial data, has been the major breakthrough in terms of utilizing computers to handle spatial data. The neighborhood characteristic describes the manner in which the particular spatial data element is related to its local neighborhood - thus making explicit for the computer the "relational" character of spatial data, as discussed above. This concept is frequently referred to as either a neighborhood relationship, or, alternatively, a topological data structure. Specification of the connection of pipes in a distribution network is an example, since each pipe thus "knows" its neighbor (connecting) pipes.

Within this overall structure, there are three basic types of spatial data elements that must be handled by a spatial data base management system:

- points (or items represented as points)
- lines (or items represented by lines)
- areas (or items represented by areas)

Of particular importance to engineering applications is the combination of point, line, and areal data into networks and tributary or service areas, as for a stream drainage system, or a water supply system. Because of the great importance of connectivity in spatial data analysis, network data may be considered to be a fourth type of data, not simply a construct of points/lines/areas.

SPATIAL WATER SUPPLY MODELING - AREAS OF POTENTIAL APPLICATION

The Water Supply Simulation Model can be used to study many issues related to water supply and water utility management. As noted above, a number of events have given rise to increased interest in examination and analysis of water supply/water utility management, for example:

- passage of the Safe Drinking Water Act
- recent droughts in the east and west and issues related to conservation
- increased concern relative to the older water distribution system of major cities
- suggestions of a relationship between water treatment practices, such as chlorination, and the formation of possibly cancer-causing trace chemicals, e.g., trihalomethanes.

These events come at a time when economic pressures, on water consumers as well as suppliers, are great. Many of the problems to be addressed are inter-related economic, engineering, and institutional ones. Water conservation, for example, is not simply a problem of reducing user demand - financing structures are traditionally such that a reduction in demand may necessitate an increase in rates charged to the consumer, to avoid shortfalls in income for debt service by the utility. Engineering problems are also involved; detection of leaks, prioritization of repair projects, impacts of reduced flow on the hydraulic capacity of sewers to transport waste, all come into play. Similar inter-related problems are shown in another arena, that of regionalization of

small water supply systems. While it has been suggested that economies of scale associated with a regional water system would benefit small system consumers in terms of price, quality, and reliability, there are many institutional barriers at the local level to such regionalization. At the same time, many of the assumptions about economies of scale of regionalization are open to question, as increased distribution costs offset advantages gained from larger treatment plants.

Another question frequently raised relative to water utilities is the issue of revenue structures. The commonly-used declining block rate, in which lower unit costs are associated with large quantities of use, has come under fire (in electric utilities as well as water utilities) as discouraging conservation. The concept of "cost-of-service pricing", by which the consumer pays, not a flat rate, but a rate commensurate with the actual costs of delivering water, has been advanced as a possible alternative revenue structure. The concept of cost-of-service pricing, while powerful in itself, raises a large number of issues associated with the water supply, including the relative subsidies that exist between peak and off-peak users, between users in one geographic area and those in another, and between beneficiaries of fire protection (in the form of reduced fire insurance, and a more favorable building/zoning climate) and consumptive users of water.

ISSUES IN COST ALLOCATION

Economic studies of water supply systems most frequently examine the system as a whole; in fact, there is little data on component economic costs, and most water utilities do not account for costs in such a way that capital, operation, and maintenance costs of specific hydraulic elements can be identified. From a spatial point of view, however, certain hydraulic elements exist solely to satisfy certain geographic classes of user. Similarly, other groups

of elements, or portions of element capacity, may be viewed as existing primarily to satisfy peak usage periods. Thus, in order to develop approaches of cost-of-service estimation, it is necessary to assign cost components to the various hydraulic elements of the system, and then to define an allocation policy that associates the individual cost elements with demand at a particular location in the network. A complete theoretical exposition of cost formulation is presented in Volume II of this report. The WSSM currently makes use of a linear allocation procedure for cost, described elsewhere in this report, but other allocation procedures are possible. Similarly, a number of simplifying assumptions about water supply system behavior are necessary in order to initiate the spatial examination of costs.

For purposes of model development, a water supply system is viewed as having two major types of physical, and associated cost, components: acquisition-treatment (A-T) and transmission-distribution (T-D). Water supply design practices have encouraged this conceptual separation by translating it into practice - acquisition and treatment functions are localized at a few sites; regionalization assumes that significant economies of scale are to be derived from having larger plants, serving a larger area. A spatial analytical approach can focus attention on some questions that are raised by adhering to this framework. At a certain point, the transmission-distribution system costs associated with serving a large area may offset the acquisition-treatment economies of scale associated with regionalization. Similarly, the assumption that all users are serviced by a distribution system containing water that has been acquired and treated at a distant location will not always lead to the least cost service - a water consumer in a distant or inaccessible location might better be served by on-site acquisition or treatment, and correspondingly

smaller distribution costs (e.g., a cistern). Public health considerations have generally favored the centralized approach, which is also assumed to be more economical, but such an approach is not the only possible one.

A simple theoretical/empirical spatial analysis of regional economics of water distribution serves to demonstrate the power of spatial analysis perspectives, coupled with mathematical models. This analysis, carried out as an adjunct to the early-state development of the WSSM, examines the cost tradeoff between economies of scale for A-T components, vs. increased costs for T-D components, as the water supply service area is expanded. Existence of cost economies of scale for the central plant (acquisition-treatment) components has been well documented in the literature.[7,15] From data in a study conducted for the USEPA this relationship is again verified for the total cost of acquisition and treatment to be:[16]

$$TC_1 = \underset{(0.065)}{512.8\ Q^{.77}} \qquad (R^2 = .610) \tag{7}$$

where

Q = quantity of revenue producing water, million gallons/year;

TC_1 = total cost of acquisition and treatment, $/year.

The exponent of Q (.773 < 1) indicates that scale economies exist in this data set for the acquisition and treatment component.

Equation 7 can be reformulated in terms of unit costs as follows:

$$TUC_1 = 512\ Q^{-0.23} \tag{8}$$

where

$$TUC_1 = TC_1/Q \tag{9}$$

With respect to the transmission/distribution component, costs at any point in the system can be postulated to be a function of flow as follows (based on regression analysis):

$$TC_2 = 408.1\ Q_p^{0.82} \qquad (R^2 = 0.84) \qquad (10)$$

where

TC_2 = total cost for transmission and distribution for a given area within the system:

Q_p = consumption in million gallon per year at a point in the system.

Rewriting equation 10 in terms of unit cost yields:

$$TUC_2 = 408.1\ Q_p^{-0.18} \qquad (11)$$

where

TUC_1 = unit cost for transmission/distribution in $/million gallon at a point in the system

If the assumption is made that flow at a point is a function of population density and per capita water use, then Q_p can be written as:

$$Q_p = CP_d \qquad (12)$$

where

C = annual capital consumption in mil/capita/yr; and

P_d = population density for a given area in people/sq mile.

It is reasonable to assume that population density will vary over the service area. One assumption concerning this variation is as follows:[16]

$$P_d = Ke^{-\lambda r} \qquad (13)$$

where

K = population density at a central point in the area in people/sq mile

λ = % change in population density over distance; and

r = distance in miles from a central point.

Substituting equations 12 and 13 into equation 11 yields:

$$TUC_2 = 408.1\ (CKe^{-\lambda r})^{-0.18} \qquad (14)$$

The flow in equation 7 is for the entire utility. Therefore equation 12 for flow at a point must be integrated over the entire service area. Assuming a flat and circular service area leads to the following integration:

$$Q = [(\Theta' CK)/\lambda^2]\ [1-e^{-\lambda d}(1+\lambda d)] \qquad (15)$$

where

Θ' = angle of integration in radians

d = the limit of integration in miles

The total unit cost equation is therefore as follows:

$$TUC = 512.8\ [C\Theta'\ K[1-e^{-\ d}(1+\lambda d)^{\lambda-1}] \quad /\lambda^2 + [408.1(CK)^{\beta-1}]/\beta^2]\ [1-e^{-\ \beta d}\ (1+\beta\lambda d)]/[1-e^{-\lambda d}(1+\beta\lambda d)]. \qquad (16)$$

TUC = total unit cost for water service in $/million gallons.

The following assumption were used as typical of the WSSM reference service area:

C = 150 gal/capita/day

K = 15,000 people/sq mi

λ = 0.12

α = 0.77

β = 0.82

Θ'=

Figure 25 shows how the unit cost varies over the service area with respect to the distance the water must be transmitted. As can be seen, the unit cost decreases until the 7 mile point, and then rises rapidly. along this line both quantity and distance change. Figure 25 clearly shows that there are limitations to the least-cost size of water utility service area. This demonstrates that a minimum unit cost of supply exists in relation to distance. The implication for regional water supply is that economies of scale gained by a centralized plant dissipate in the transmission/distribution system about eight miles from the plant. After that point, unit costs continue to rise. Therefore, regionalization of water utilities may not be apriori justified by the economies of scale argument. It depends significantly upon how close the respective utilities are, as well as the difference between marginal costs of add-on treatment technologies

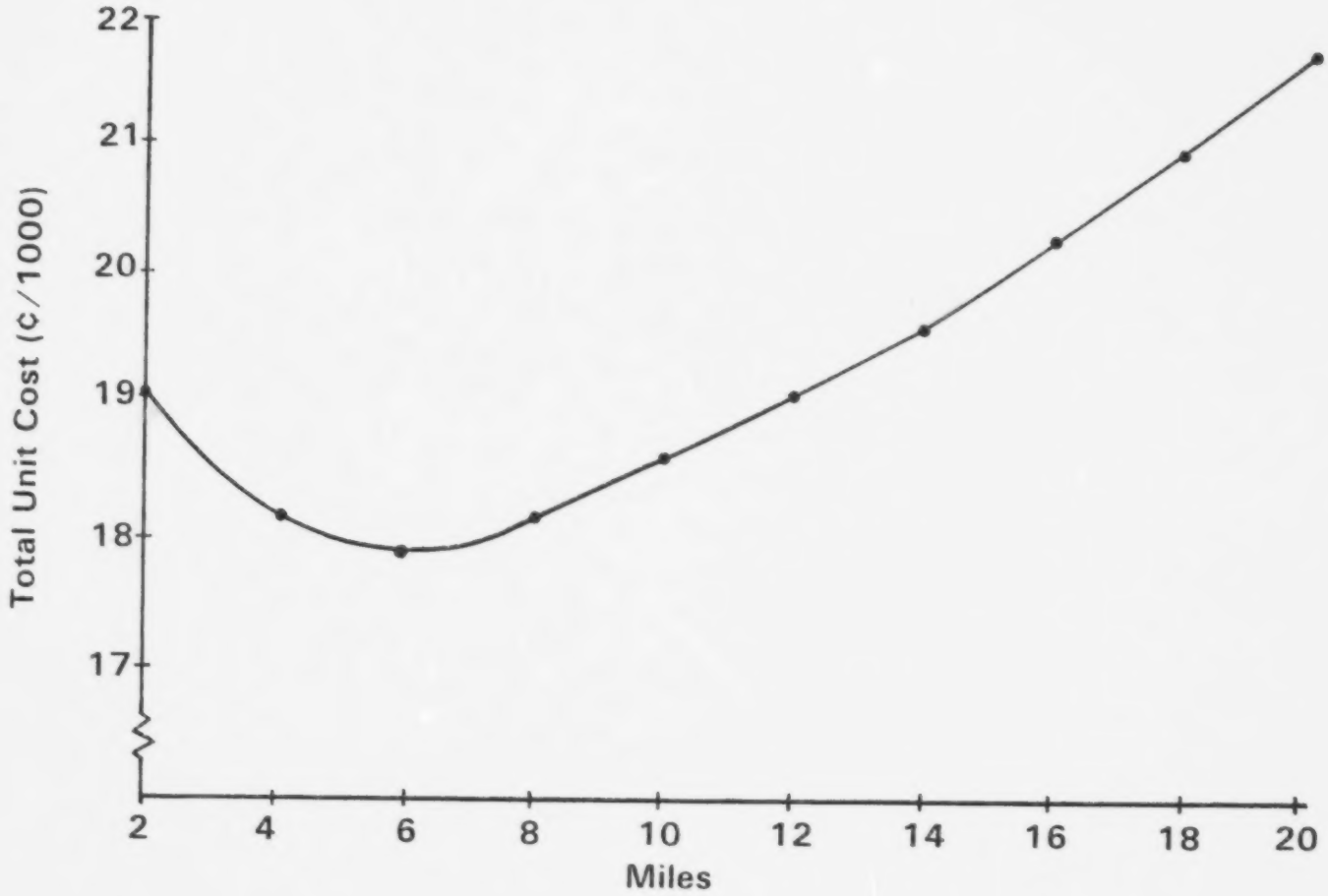


FIGURE 25. COST OF WATER VERSUS DISTANCE TRANSPORTED

and the additional costs of transmission/distribution system expansion to link the utilities. While it is obvious that the 8-mile distance may vary in specific circumstances, the limit on economic benefits of regionalization is clear from this analysis.

SYSTEMS DYNAMICS

Cost allocation, as currently implemented in the WSSM, is based on steady-state assuptions. When considering an average flow, steady-state scenario, it is assumed that link and nodal costs can be developed or estimated with little difficulty. Consideration of peak/off-peak flows, however, presents many interesting questions.

A water supply system is a dynamic system. The "peak/off-peak" distinction is an attempt to deal with system dynamics as two "steady-state" conditions. There are inherent conceptual problems associated with this distinction, e.g. the role of storage tanks (i.e. what is the meaning of a storage tank in a steady-state situation?). In theory, under a pure steady-state situation, no tanks are required, because all demands are constant. Tanks may exist for purposes of load-leveling or to provide additional storage capacity in the system, for example to handle fire flows. When tanks are included in a steady-state analysis, they will either be continuously filling or continuously emptying. Under a peak demand situation for a properly designed system, tanks should be discharging; under an average flow situation, tanks should not be active at all, and should be filling under a low flow situation. Obviously, this may not be the case in real systems.

The above discussion indicates some of the conceptual difficulities associated with an attempt to define equity-based cost allocations in water distribution systems. Real-world systems are not "optimal" in design - they represent the result of servicing a changing growth pattern, applying engineering tradition, and observing economic and political considerations. The system,

in place, however, does function as a provider of services and as a generator of revenue, and, as the foregoing has demonstrated, the benefits as they accrue in space and time are not always commensurate with the revenues - accordingly, the water distribution system also serves, in some measure, as an income redistributor. While there is no clear path to resolve this issue, the existence of a structure such as the WSSM does provide the opportunity to qualify and perform experimental simulations relating to many of these complex issues of cost allocation.

SUMMARY AND CONCLUSIONS

The development of a spatially oriented water supply simulation model has been described. The model can be used to provide cost allocation, time of travel and contaminant concentration information in a water supply network. Contaminant concentration in this case implies conservative contaminants, such as inorganics or particulate matter. Development of this model provides a tool with which to acquire additional insight into the treatment and delivery of water. Some of the qeustions to be addressed in future studies include:

1 exploration of the impact of design for fire protection, and the manner in which beneficiaries of this "non-consumptive" use are assessed in revenue structures

- further exploration of peak/off peak considerations, and simulation of pricing strategies
- use of concentration and time-of-travel capabilities of the WSSM to simulate quality differences in multiple source systems, and to study transport and decay of water-borne pollutants through the system
- further examination of spatial methodologies for parameterizing hydraulic network analysis models in a simple manner
- use of the graphic capbilities of WSSM in other arenas, such as pipe break data display.

In addition, a major future direction involves feedback of the water supply network on land development patterns, and inter-relationship between the water supply network and the waste collection network. The system can be conceptualized as one in which two networks (water supply and waste disposal) are placed on a spatial pattern of development. Water is supplied to land through the water supply network, converted in quantity and quality depending upon the particular land use mix and recovered through the waste collection system. Such a conceptual approach allows for integrated analysis of complex growth scenarios, and is further applicable to other situations, such as irrigated agriculture.

In short, there are a wide variety of future directions for application of the technology of the WSSM, and for expansion of the capabilities of that technology itself.

REFERENCES

1. Breidenbach, A. W., "Regulations: Reactions and Resolution," Journal of the American Water Works Association, Vol. 68, No. 2, Feb. 1976, pp. 77-82.

2. Angotti, T. R., "Planning for Regional Wastewater Systems", Growth and Change: A Journal of Regional Development, Vol. 6, No. 2, Apr., 1975, pp. 36-42.

3. Clark, Robert M., "Water Supply Regionalization: A Critical Evaluation", Journal of the Water Resources Planning and Management Division, ASCE, Vol. 105, No. WR 2, Proc. Paper 14824, September, 1979, pp. 279-294.

4. Dajani, J. S., and Gemmel, R. S., "Economic Guidelines of Public Utilities Planning," Journal of the Urban Planning and Development Division, ASCE, Vo. 99, No. UP2, Proc. paper 9977, Sept., 1976, pp. 171-182.

5. Marks, D. H., Revelle, C. S., and Liebman, J. C., "Mathematical Models of Location: A Review" Journal of the Urban Planning and Development Division, ASCE, Vol. 96, No. UP 1, Proc. Paper 7164, Mar. 1970, pp. 81-93.

6. Konig, L., "The Cost of Water Treatment by Coagulation, Sedimentation, and Rapid Sand Filtration," Part 1, Report for U.S. Public Health Service, Division of Water Supply and Pollution Control, Technical Services Branch, Jan. 1966.

7. Orlob, G. T., and Lindorf, M. R., "Cost of Water Treatment in California," Journal of the American Water Works Association, Vol. 20, Jan. 1958, pp. 45-55.

8. R. H. Coase, "The Economies of Uniform Pricing Systems," Manchester School of Economics and Social Studies, Vol. 15, No. 5 (May 1947), pp. 139-56.

9. L. T. Ford and L. T. Warford, "Cost Functions for the Water Industry," Journal of Industrial Economics, Vol. 18, No. 11 (November 1969), pp. 53-63.

10. P. F. Linaweaver and C. Clark, "Costs of Water Transmission", Journal of the American Water Works Association, Vol. 56, No. 12 (December 1964), pp. 1549-60.

11. Rao, H. S., Bree, D. W. Sr., Benzri, R., "Extended Period Simulation of Water Distribution Networks", February 1974, National Technical Information Service Report PB 230 148.

12. Water User's Manual, University of Waterloo, Waterloo Research Institute, Waterloo, Ontario, Canada.

13. W. E. Gates and Associates, "Preliminary Engineering Report, New Vienna Water System Improvements", Batavia, Ohio, July 1980.

14. Gumerman, R. C., Culp, R. L., and Hansen, S. P., Estimating Water Treatment Costs, Volume I - Summary, Environmental Protection Technology Research Series, EPA-600/2-79-162a, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

15. Martin, James, Computer Data Base Organization, Prentice-Hall, 1975.

16. Clark, Robert M., Machesko, John A., and Stevie, Richard G., "Cost of Water Supply: Selected Case Studies," Journal of the Environmental Engineering Division, ASCE, Vol. 105, No. EC 1, Proc. Paper 14365, February, 1979, pp. 89-100.

17. Clark, Robert M. and Stevie, Richard G., "A Water Supply Cost Model Incorporating Spatial Variables" Land Economies, Vol. 57, No. 1, February 1981, pp. 18-32.